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MULTI-CRITERIA ANALYSIS IN NAVAL SHIP DESIGN

by

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March 2005

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Numerous optimization problems involve systems with multiple and often contradictory criteria. Such contradictory criteria have been an issue for marine/naval engineering design studies for many years. This problem becomes more important when one considers novel ship types with very limited or no operational record. A number of approaches have been proposed to overcome these multiple criteria design optimization problems. This Thesis follows the Parameter Space Investigation (PSI) technique to address these problems. The PSI method is implemented with a software package called MOVI (Multi-criteria Optimization and Vector Identification). Two marine/naval engineering design optimization models were investigated using the PSI technique along with the MOVI software. The first example was a bulk carrier design model which was previously studied with other optimization methods. This model, which was selected due to its relatively small dimensionality and the availability of existing studies, was utilized in order to demonstrate and validate the features of the proposed approach. A more realistic example was based on the "MIT Functional Ship Design Synthesis Model" with a greater number of parameters, criteria, and functional constraints. A series of optimization studies conducted for this model demonstrated that the proposed approach can be implemented in a naval ship design environment and can lead to a large design parameter space exploration with minimum computational effort.

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I. INTRODUCTION

Numerous optimization problems involve systems with multiple and often "contradictory" criteria. Such contradictory criteria have been an issue for marine/naval engineering design studies for many years. This problem becomes more important when one considers novel ship types with very limited or no operational record. A number of approaches have been proposed to overcome these multiple criteria design optimization problems. This Thesis follows the Parameter Space Investigation (PSI) technique, which originated in the former Soviet Union, to address these problems. The PSI method is implemented with a software package called MOVI (Multi-criteria Optimization and Vector Identification).

Multi-criteria analysis of a ship design model using the PSI method was first performed by Dr. O.M. Berezanskii and Dr. Y.N. Semenov, from the State Sea Technical University, Saint Petersburg. The study was intended to improve the performance criteria of a prototype ship, UT-704 which was built by ULSTEIN group in Norway for the oil and gas industry fleet. The performance criteria were tonnage, speed, capital investments, and operational costs. The statistical data on this type of ships was used to choose the design variable constraints. As a result, the prototype has been considerably improved. [3]

Chapter II of this Thesis provides an overview of the Parameter Space Investigation (PSI) technique. Chapter III presents the multi-criteria analysis of a bulk carrier design model with MOVI software. This model was previously studied with other optimization methods by Michael G. Parsons and Randall L. Scott, from the University of Michigan. It was selected due to its relatively small dimensionality and the availability of existing studies, and was utilized in order to demonstrate and validate the features of the proposed approach.

Chapter IV presents a more realistic example based on the "MIT Functional Ship Design Synthesis Model" with a greater number of parameters, criteria, and functional constraints. This model was a modified version of the Axiomatic Design Model created by John Szatkowski, from the Massachusetts Institute of Technology. A series of

optimization studies were conducted for this model to demonstrate that the proposed approach can be implemented in a naval ship design environment and can lead to a large design parameter space exploration with minimum computational effort.

The PSI studies conducted by Roman B. Statnikov were taken as the main reference of this thesis.

II. PARAMETER SPACE INVESTIGATION METHOD

This chapter summarizes the general methodology of the Parameter Space Investigation technique as delineated in References [1] to [4]. The same notation and definitions are used in order to maintain consistency.

Mathematical formulation of the multi-criteria optimization problems is essential to comprehend the Parameter Space Investigation (PSI) technique. In this method, it is assumed that "the system is based on r design variables, which form a point in r-dimensional space, i.e., a vector of design variables". The design variable vector has the following form:

$$\alpha = (\alpha_1, \ldots, \alpha_r). \tag{2.1}$$

For example, there are six design variables for the bulk carrier design optimization model, which will be discussed in the next chapter. These variables are length (L), beam (B), depth (D), draft (T), speed (V_k), and block coefficient (C_B). The design variable vector for this model will be $\alpha = (L, B, D, T, V_k, C_B)$.

Each design variable has its own reasonable boundary. For example, the length of a ship can not be 3000 meters, nor can the block coefficient be greater than one. The design variable constraints can be symbolized as

$$\alpha_j^* \le \alpha_j \le \alpha_j^{**}, \quad j = 1, \ldots, r, \tag{2.2}$$

where α_j^* and α_j^{**} are the lower und upper acceptable values corresponding to the variable α_j. The design variable space, which is defined by the design variable constraints, forms a kind of "Parallelepiped" represented by "Π" in the r-dimensional space. The dictionary definition of a "Parallelepiped" is: "a 6-faced polyhedron all of whose faces are parallelograms lying in pairs of parallel planes" [Merriam-Webster's 11th Collegiate Dictionary]. The "Parallelepiped" is used as a term in PSI method, since the design variable space can be illustrated at most in three dimensions. If there were two design variables, $\alpha = (\alpha_1, \alpha_2)$, the design variable constraints would be written as

$\alpha_1^* \le \alpha_1 \le \alpha_1^{**}$ and $\alpha_2^* \le \alpha_2 \le \alpha_2^{**}$. The design variable space which is defined by these constraints would be two-dimensional which is illustrated in Figure 1.

Every design optimization problem has a number of "functional relations", which are functions of the design variables. The functional relations are not optimized. They are only subject to "functional constraints". For example, length to beam ratio can be a functional relationship for a ship design model that has an acceptable range (functional constraints) for every ship type. The functional constraints can be presented as

$$C_l^* \le f_l(\alpha) \le C_l^{**}, \quad l = 1,\ldots,t, \tag{2.3}$$

where $f_l(\alpha)$ represents the functional relations, and C_l^* and C_l^{**} are the lower and upper suitable values of these functional relationships respectively. The design variable and the functional constraints jointly generate a subset G in Π, which satisfies both. The two-dimensional illustration of the subset G is presented in Figure 2.

The performance criteria, which have to be either minimized or maximized, are the characteristics of the design model. The performance criteria are subject to criteria constraints. Assuming the performance criteria are functions of the design variables, the "criteria constraints" can be written as

$$\Phi_v(\alpha) \le \Phi_v^{**}, \quad v = 1,\ldots,k, \tag{2.4}$$

where $\Phi_v(\alpha)$ represents the performance criterion. Φ_v^{**} is the worst value of $\Phi_v(\alpha)$. The "less than or equal to" sign is used in Equation (2.4) because the minimization is the common form for demonstration purposes. Note that maximizing a criterion is the same operation as minimizing the negative of it [5]. Unlike the functional constraints, the criteria constraints are selected during the analysis of the problem. They are not rigid, i.e., the designer can continually determine and revise the worst sensible value for them. The criteria constraints along with the design variable and the functional constraints create a feasible set D, which satisfies all of them. The feasible solution set D is a subset of G, and therefore $D \subset G \subset \Pi$. Each vector in the feasible solution set D represents a potential design solution for the multi-criteria optimization problem. The two-dimensional illustration of the subset D is presented in Figure 3.

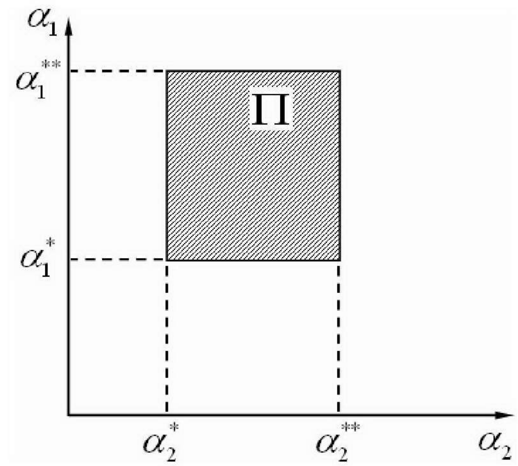

Figure 1 Parallelepiped (From Ref. [1].)

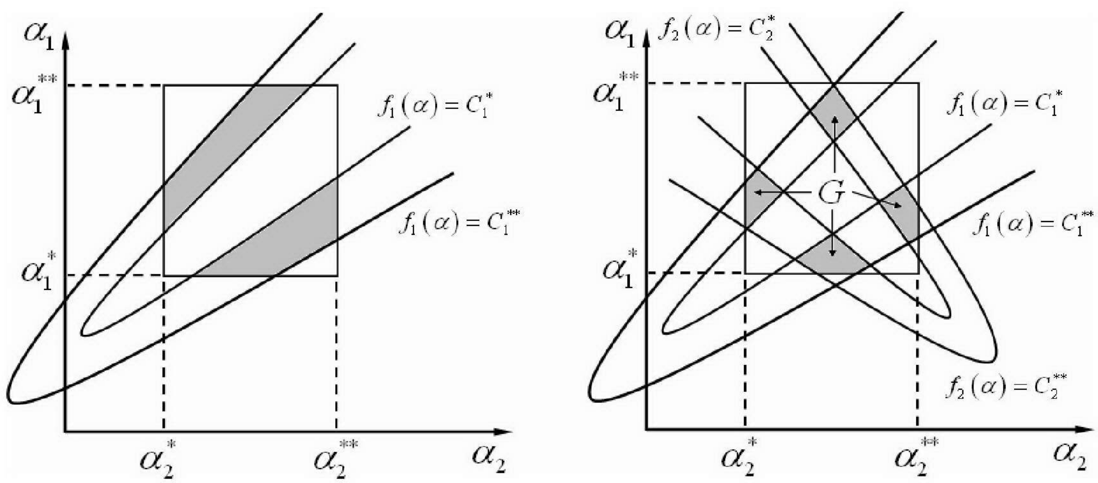

Figure 2 Subset G in Π after Imposing the Functional Constraints (After Ref. [1].).

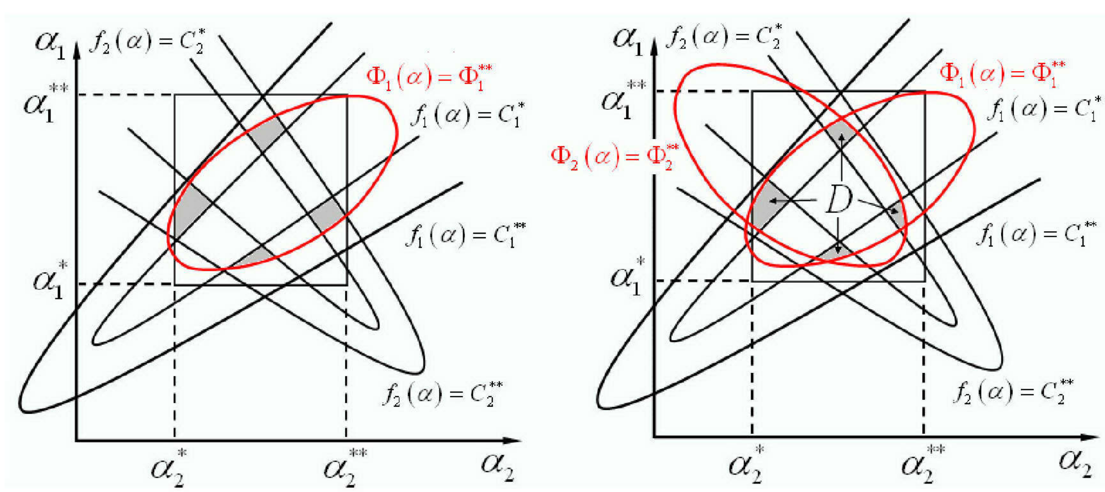

Figure 3 Feasible Set D after Imposing the Criteria Constraints (After Ref. [1].).

The performance criteria can also be represented as

$$\Phi(\alpha)=\left(\Phi_1(\alpha),\ldots,\Phi_k(\alpha)\right), \tag{2.5}$$

which is called the "criterion vector". The optimal design solution among the vectors in the feasible solution set D can be found by determining a "Pareto optimal set", $P \subset D \subset G \subset \Pi$, which has the following formulation and definition:

$$\Phi(P)=\min_{\alpha \in D}\Phi(\alpha) \tag{2.6}$$

"A point $\alpha^0 \in D$, is called the Pareto optimal point if there exists no point $\alpha \in D$ such that $\Phi_v(\alpha) \le \Phi_v(\alpha^0)$ for all $v=1,\ldots,k$ and $\Phi_{v_0}(\alpha) < \Phi_{v_0}(\alpha^0)$ for at least one $v_0 \in \{1,\ldots,k\}$. A set $P \subset D$ is called a Pareto optimal set if it consists of Pareto optimal points." [1]

Assume that the criterion vector contains two criteria, $\Phi(\alpha)=\left(\Phi_1(\alpha),\Phi_2(\alpha)\right)$, which are both minimized. The Pareto optimal set $P(\Pi)$ would look like the curve shown in Figure 4. $P(\Pi)$ means that the criteria values of the Pareto optimal set are computed using the "parallelepiped" in Figure 1. Φ^P is the "prototype", in other words, the desired design or the existing design that needs to be improved.

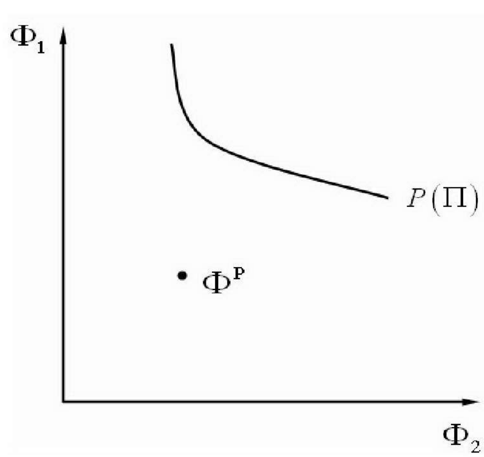

Figure 4 Pareto Optimal Set (After Ref. [1].).

The general strategy to determine the initial parallelepiped is to put the prototype in the center of it, unless the design variable constraints are already given [1]. For each parameter, the upper bound can be found by adding a reasonable value, ε_j, to the corresponding prototype parameter value. Likewise, the lower bounds can be found by subtracting the same reasonable value (Equation 2.7).

$$\alpha_j^{\mathrm{P}} - \varepsilon_j \le \alpha_j \le \alpha_j^{\mathrm{P}} + \varepsilon_j, \quad j = 1,\ldots,r \tag{2.7}$$

After the first analysis, the results may be unsatisfactory. The Pareto optimal set might need to be closer to the desired prototype. In fact, it is possible that no vectors will enter the feasible solution set. The problem statement, i.e., the design variable and functional and criteria constraints must be reviewed and corrected to improve the results. Changing the design variable constraints leads to a new parallelepiped. The new Pareto optimal set calculated by this parallelepiped might be a better solution. Assume that the Pareto optimal set, $P(\Pi)$, in Figure 4 needs improvement. Figure 5 and Figure 6 demonstrate this process. The design variable constraints are redefined to form the new parallelepiped, Π_1, and this parallelepiped forms the new Pareto optimal set, $P(\Pi_1)$, which is better, but still insufficient. Another correction of the design variable constraints leads to the third parallelepiped, Π_2, which forms the third Pareto optimal set, $P(\Pi_2)$, which is a more acceptable solution. In fact, by combining the curves $\overset{\frown}{\mathrm{AB}} \subset P(\Pi_2)$, and $\overset{\frown}{\mathrm{BC}} \subset P(\Pi_1)$ the most preferable Pareto optimal set can be created.

The functional relations which do not have rigid functional constraints may be assumed to be "pseudo-criteria" at the beginning of the analysis (Equation 2.8) [1]. The functional relations must be minimized for the upper functional constraint, and maximized for the lower functional constraint. Then the appropriate values of the pseudo-criteria constraints can be introduced in place of the functional constraints.

$$\Phi_{k+l}(\alpha) = f_l(\alpha), \quad l = 1,\ldots,t, \tag{2.8}$$

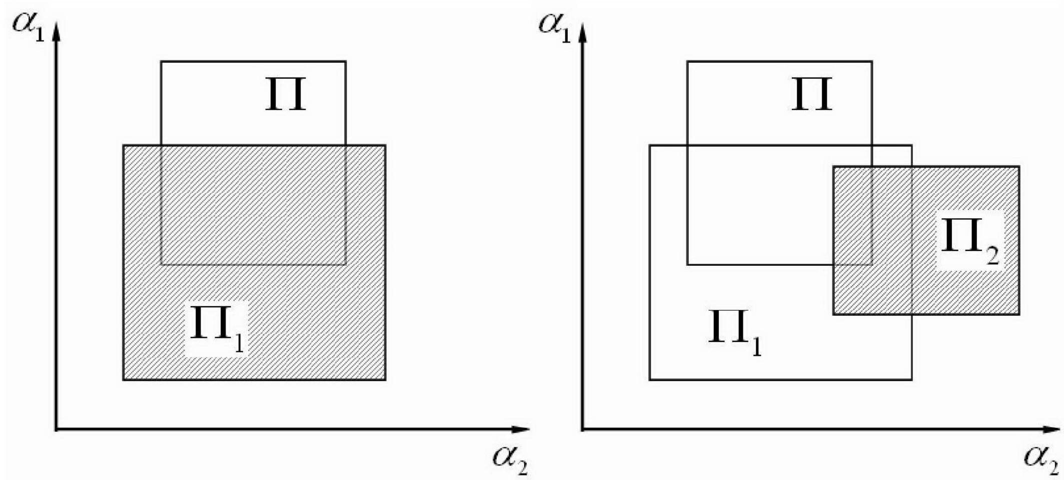

Figure 5 Design Variable Spaces after Each Analysis (After Ref. [1].).

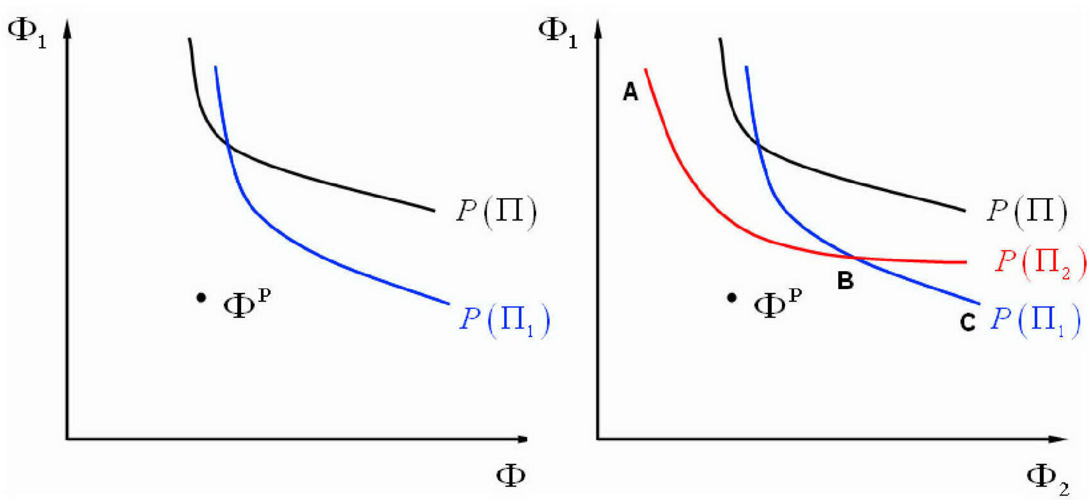

Figure 6 Pareto Optimal Sets after Each Analysis (After Ref. [1].).

The PSI method uses uniformly distributed LP_τ sequences or random number generators to produce the vectors (points) in the design variable space [1]. The coordinates of the vectors $\alpha^i = \left(\alpha_1^i, ..., \alpha_r^i\right) \in \Pi$ are calculated using the Cartesian coordinates of LP_τ sequences for the points $Q_i = \left(q_{i,1}, q_{i,2}, \ldots, q_{i,r}\right)$ (Equation 2.9).

$$\alpha_j^i = \alpha_j^* + q_{i,j}\left(\alpha_j^{**} - \alpha_j^*\right), \quad j = 1, 2, ..., r \tag{2.9}$$

The Cartesian coordinates of LP_τ sequences for the first sixteen 20-dimensional points (20 design variables) are presented in Table 1 ($r = 20, \quad i = 1, \ldots, 16$).

i	$j=1$ / $j=6$ / $j=11$ / $j=16$	$j=2$ / $j=7$ / $j=12$ / $j=17$	$j=3$ / $j=8$ / $j=13$ / $j=18$	$j=4$ / $j=9$ / $j=14$ / $j=19$	$j=5$ / $j=10$ / $j=15$ / $j=20$
$i=1$	1/2	1/2	1/2	1/2	1/2
	1/2	1/2	1/2	1/2	1/2
	1/2	1/2	1/2	1/2	1/2
	1/2	1/2	1/2	1/2	1/2
$i=2$	1/4	3/4	1/4	3/4	1/4
	3/4	1/4	3/4	3/4	1/4
	3/4	1/4	3/4	1/4	3/4
	1/4	1/4	3/4	1/4	3/4
$i=3$	3/4	1/4	3/4	1/4	3/4
	1/4	3/4	1/4	1/4	3/4
	1/4	3/4	1/4	3/4	1/4
	3/4	3/4	1/4	3/4	1/4
$i=4$	1/8	5/8	7/8	7/8	5/8
	1/8	3/8	3/8	7/8	5/8
	5/8	7/8	7/8	1/8	3/8
	3/8	7/8	5/8	1/8	1/8
$i=5$	5/8	1/8	3/8	3/8	1/8
	5/8	7/8	7/8	3/8	1/8
	1/8	3/8	3/8	5/8	7/8
	7/8	3/8	1/8	5/8	5/8
$i=6$	3/8	3/8	5/8	1/8	7/8
	7/8	1/8	5/8	1/8	7/8
	3/8	5/8	1/8	3/8	5/8
	1/8	5/8	3/8	3/8	7/8
$i=7$	7/8	7/8	1/8	5/8	3/8
	3/8	5/8	1/8	5/8	3/8
	7/8	1/8	5/8	7/8	1/8
	5/8	1/8	7/8	7/8	3/8
$i=8$	1/16	15/16	11/16	5/16	3/16
	1/16	7/16	9/16	13/16	11/16
	1/16	3/16	7/16	9/16	5/16
	13/16	13/16	11/16	3/16	15/16
$i=9$	9/16	7/16	3/16	13/16	11/16
	9/16	15/16	1/16	5/16	3/16
	9/16	11/16	15/16	1/16	13/16
	5/16	5/16	3/16	11/16	7/16
$i=10$	5/16	3/16	15/16	9/16	7/16
	13/16	3/16	5/16	1/16	15/16
	13/16	7/16	11/16	13/16	9/16
	9/16	9/16	7/16	7/16	3/16
$i=11$	13/16	11/16	7/16	1/16	15/16
	5/16	11/16	13/16	9/16	7/16
	5/16	15/16	3/16	5/16	1/16
	1/16	1/16	15/16	15/16	11/16
$i=12$	3/16	5/16	5/16	11/16	9/16
	3/16	1/16	15/16	3/16	1/16
	11/16	13/16	9/16	11/16	3/16
	11/16	3/16	1/16	1/16	13/16
$i=13$	11/16	13/16	13/16	3/16	1/16
	11/16	9/16	7/16	11/16	9/16
	3/16	5/16	1/16	3/16	11/16
	3/16	11/16	9/16	9/16	5/16
$i=14$	7/16	9/16	1/16	7/16	13/16
	15/16	5/16	3/16	15/16	5/16
	7/16	9/16	5/16	15/16	15/16
	15/16	7/16	13/16	5/16	1/16
$i=15$	15/16	1/16	9/16	15/16	5/16
	7/16	13/16	11/16	7/16	13/16
	15/16	1/16	13/16	7/16	7/16
	7/16	15/16	5/16	13/16	9/16
$i=16$	1/32	17/32	13/32	7/32	15/32
	9/32	31/32	9/32	3/32	27/32
	15/32	29/32	21/32	23/32	19/32
	11/32	13/16	7/32	13/32	17/32

Table 1 The Cartesian Coordinates of LP_τ Sequences for the First Sixteen 20-Dimensional Points, $Q_i = \left(q_{i,1}, q_{i,2}, \ldots, q_{i,20}\right)$, $i = 1, \ldots, 16$ (After Ref. [4].).

j	α_j^*	α_j^{**}	$\alpha_j^{**} - \alpha_j^*$	j	α_j^*	α_j^{**}	$\alpha_j^{**} - \alpha_j^*$
1	2	7	5	11	124	157	33
2	23	45	22	12	33	67	34
3	3	9	6	13	4	7	3
4	45	79	34	14	5	21	16
5	13	90	77	15	34	39	5
6	200	230	30	16	12	71	59
7	15	28	13	17	64	68	4
8	56	112	56	18	1123	1500	377
9	2	25	23	19	87	200	113
10	17	19	2	20	3400	3700	300

Table 2 The Design Variable Constraints (Example).

Assume that the design variable constraints are like those in Table 2. The design variable space with 16 design variable vectors (points) can be computed using the Cartesian coordinates of the LP_τ sequences tabulated in Table 1, and Equation 2.9 (See Table 3 for the results). The basic steps to compute a point $\alpha^9 = \left(\alpha_1^9, \alpha_2^9, \ldots, \alpha_{20}^9\right)$ are presented as follows.

$$Q_{9,15} = \left(q_{9,1}, q_{9,2}, \ldots, q_{9,20}\right) = \left(\frac{9}{16}, \frac{7}{16}, \ldots, \frac{7}{16}\right) \tag{2.10}$$

$$\alpha_1^9 = 2 + \frac{9}{16}(7-2) = 4.813, \quad \alpha_2^9 = 23 + \frac{7}{16}(45-23) = 32.625, \ldots \tag{2.11}$$

$$\alpha^9 = \left(\alpha_1^9, \alpha_2^9, \ldots, \alpha_{20}^9\right) = (4.813, 32.625, \ldots, 3531.250) \tag{2.12}$$

$i=1$	4.500	34.000	6.000	62.000	51.500	$i=9$	4.813	32.625	4.125	72.625	65.938
	215.000	21.500	84.000	13.500	18.000		216.875	27.188	59.500	9.188	17.375
	140.500	50.000	5.500	13.000	36.500		142.563	56.375	6.813	6.000	38.063
	41.500	66.000	1311.500	143.500	3550.000		30.438	65.250	1193.688	164.688	3531.250
$i=2$	3.250	39.500	4.500	70.500	32.250	$i=10$	3.563	27.125	8.625	64.125	46.688
	222.500	18.250	98.000	19.250	17.500		224.375	17.438	73.500	3.438	18.875
	148.750	41.500	6.250	9.000	37.750		150.813	47.875	6.063	18.000	36.813
	26.750	65.000	1405.750	115.250	3625.000		45.188	66.250	1287.938	136.438	3456.250
$i=3$	5.750	28.500	7.500	53.500	70.750	$i=11$	6.063	38.125	5.625	47.125	85.188
	207.500	24.750	70.000	7.750	18.500		209.375	23.938	101.500	14.938	17.875
	132.250	58.500	4.750	17.000	35.250		134.313	64.875	4.563	10.000	34.313
	56.250	67.000	1217.250	171.750	3475.000		15.688	64.250	1476.438	192.938	3606.250
$i=4$	2.625	36.750	8.250	74.750	61.125	$i=12$	2.938	29.875	4.875	68.375	56.313
	203.750	19.875	77.000	22.125	18.250		205.625	15.813	108.500	6.313	17.125
	144.625	62.750	6.625	7.000	35.875		146.688	60.625	5.688	16.000	34.938
	34.125	67.500	1358.625	101.125	3437.500		52.563	64.750	1146.563	94.063	3643.750
$i=5$	5.125	25.750	5.250	57.750	22.625	$i=13$	5.438	40.875	7.875	51.375	17.813
	218.750	26.375	105.000	10.625	17.250		220.625	22.313	80.500	17.813	18.125
	128.125	45.750	5.125	15.000	38.375		130.188	43.625	4.188	8.000	37.438
	63.625	65.500	1170.125	157.625	3587.500		23.063	66.750	1335.063	150.563	3493.750
$i=6$	3.875	31.250	6.750	49.250	80.375	$i=14$	4.188	35.375	3.375	59.875	75.563
	226.250	16.625	91.000	4.875	18.750		228.125	19.063	66.500	23.563	17.625
	136.375	54.250	4.375	11.000	37.125		138.438	52.125	4.938	20.000	38.688
	19.375	66.500	1264.375	129.375	3662.500		67.313	65.750	1429.313	122.313	3418.750
$i=7$	6.375	42.250	3.750	66.250	41.875	$i=15$	6.688	24.375	6.375	76.875	37.063
	211.250	23.125	63.000	16.375	17.750		213.125	25.563	94.500	12.063	18.625
	152.875	37.250	5.875	19.000	34.625		154.938	35.125	6.438	12.000	36.188
	48.875	64.500	1452.875	185.875	3512.500		37.813	67.750	1240.813	178.813	3568.750
$i=8$	2.313	43.625	7.125	55.625	27.438	$i=16$	2.156	34.688	5.438	52.438	49.094
	201.875	20.688	87.500	20.688	18.375		208.438	27.594	71.750	4.156	18.688
	126.063	39.375	5.313	14.000	35.563		139.469	63.813	5.969	16.500	36.969
	59.938	67.250	1382.188	108.188	3681.250		32.281	67.250	1205.469	132.906	3559.375

Table 3 The Design Variable Vectors Computed Using LP_τ Sequences.

III. MULTI-CRITERIA ANALYSIS WITH MOVI 1.3 SOFTWARE

A. INTRODUCTION

There are many optimization studies in literature about marine/naval engineering design problems with multiple and mostly "contradictory" criteria. "Contradictory" means that enhancing the quality of some criteria causes negative effects for the other criteria. For example, maximizing the annual cargo and minimizing the light ship weight will obviously be in contradiction [5]. Many methods have been developed to find a "compromise solution", i.e., an optimum solution for these kinds of engineering problems. The Parameter Space Investigation (PSI) technique, as mentioned, is one of these methods. The PSI method is implemented with a software package called MOVI (Multi-criteria Optimization and Vector Identification) which allows the user to find solutions to these optimization problems. The optimization problems with less then nine design variables can be solved using the "Educational" version of the software (MOVI 1.3). The full edition MOVI 1.3 package should be used to optimize problems with greater than eight design variables. The potential of the computer, i.e., the computer's processing power, is important for the number of criteria to be optimized. [1&2]

A marine design optimization example with three criteria, six variables (parameters), and fourteen functional constraints taken from Reference [5] was selected to illustrate the use of the PSI method along with the MOVI software.

B. BULK CARRIER DESIGN OPTIMIZATION MODEL

The selected problem was a basic commercial ship design optimization model for bulk carriers that have deadweights between 3,000 and 500,000 tons and speeds between about 14 and 18 knots. It is not a naval ship design model. However, it was selected to demonstrate the features of MOVI software, since it is a "simplified sizing problem" with small numbers of parameter, criteria, and functional constraints. This "rough model" uses the "Admiralty coefficient method" for power assessment. The Admiralty coefficient was derived "as a function of Froude number and block coefficient". The bulk carrier design optimization model can be seen in detail in Appendix A. [5]

There are six design variables (parameters) to optimize. These parameters are as follows.

Independent variables (6):

L = length (m)

B = beam (m)

D = depth (m)

T = draft (m)

V_k = speed (knots)

C_B = block coefficient

There are three optimization criteria. The transportation cost and light ship weight were minimized, while the annual cargo was maximized. The contradictory behavior of second and third criterion is noticeable. Two different problems, Case-1 and Case-2, were offered for this model using two extra constraint sets to present a more reasonable scenario. Hence, there are eleven functional relations and fourteen functional constraints, with the additional 11th relation and 14th constraint introduced by Case-1. Since it was not investigated with the PSI method, Case-2 is not mentioned here.

Constraints (13):

$L/B \geq 6$

$L/D \leq 15$

$L/T \leq 19$

$T - 0.45\ \mathrm{DWT}^{0.31} \leq 0$

$T - 0.7\,D - 0.7 \leq 0$

$3{,}000 \leq \mathrm{DWT} \leq 500{,}000$

$0.63 \leq C_B \leq 0.75$

$14 \leq V_k \leq 18$

$F_n \leq 0.32$

$GM_T - 0.07\,B \geq 0$

Case 1: added 14th constraint

$L \leq 274.32$ m (900 ft), perhaps due to dock, lock, or turning basin limits,

minimum DWT raised from 3,000 t to 25,000 t

C. MULTI-CRITERIA OPTIMIZATION PROCESS

The bulk carrier design optimization model was first modified in MATLAB to start the optimization process by referring to the example MATLAB code provided along with the MOVI 1.3 software (MOVI\Examples\MatLab\Example_R13). Essentially, nothing was changed during this adjustment except some definitions. For instance, the parameters length (L), block coefficient (C_B), and speed (V_k) were also defined as functional relations in the problem statement. Therefore, the functional constraints for these three functional relations, i.e., parameters, were used as initial boundaries. As a result, the number of functional relations was reduced to eight and the number of functional constraints was reduced to nine. The number of parameters and criteria did not change. The MATLAB code for the bulk carrier design optimization model is in Appendix B. The review of design variables, functional relations, functional constraints, and criteria are as follows. Note that subscripts of some variables were written in normal text to conform to MATLAB notation.

Design parameters (variables):

L	= p1;	Length (m)	L <= 274.32 m
B	= p2;	Beam (m)	
D	= p3;	Depth (m)	
T	= p4;	Draft (m)	
CB	= p5;	Block coefficient, 0.63 <= CB <= 0.75	
Vk	= p6;	Speed (knots),	14 <= Vk <= 18

Functional relations:

f1	= L/B;
f2	= L/D;
f3	= L/T;
f4	= T – 0.45×DWT^0.31;
f5	= T – 0.7×D – 0.7;
f6	= DWT;
f7	= Fn;
f8	= GMT – 0.07×B;

Functional constraints:

f1	= L/B	>= 6
f2	= L/D	<= 15
f3	= L/T	<= 19
f4	= T – 0.45×DWT^0.31	<= 0
f5	= T – 0.7×D – 0.7	<= 0
f6	= DWT	<= 500,000
f6	= DWT	>= 25,000
f7	= Fn	<= 0.32
f8	= GMT – 0.07×B	>= 0

Criteria:

c1	= trc;	Transportation cost (£/t) (Minimize)
c2	= lsw;	Light ship weight (Minimize)
c3	= acrg;	Annual cargo (t/yr) (Maximize)

Fundamentally, MOVI 1.3 optimization software solves the user's mathematical models by transferring the data back and forth. It produces the "design variable vectors" and sends them to the user's model, and then gets the "values of criteria and functional relations" processed by the model (See Figure 7). [2]

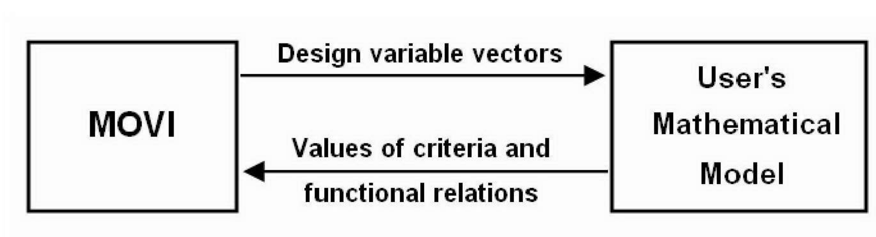

Figure 7 Data exchange between MOVI 1.3 and the user's model (From Ref. [2].).

Dynamic Link Library (DLL) files are used to establish the data transfer and computation. The DLL file takes the design variable vector from MOVI, calculates the values of criteria and functional relations, and sends them back to MOVI (See Figure 8). The MOVI installation folder has examples of Delphi 5 and Microsoft Visual C++ files to create these Dynamic Link Library (DLL) files. There is also a Visual C++ file (for the bulk carrier design optimization model) in Appendix D to generate a Dynamic Link

Library as a mathematical model, i.e., a model which calculates the values of criteria and functional relations internally without using an external program like MATLAB.

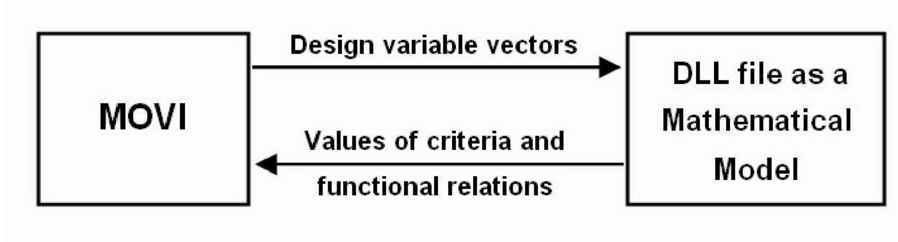

Figure 8 Data exchange between MOVI 1.3 and the DLL model (After Ref. [2].).

The files to generate Dynamic Link Libraries are so simple that intense knowledge of Visual C++ is not necessary. Basically, a compiler, such as Microsoft Visual C++ 6.0 or newer is required. The example folder of MOVI (MOVI\Examples\VisualC++) has Visual C++ files for the "Oscillator" example problem discussed in Reference [2]. Referring to those files, a folder named "Ship model" is created for the bulk carrier design optimization model (See Figure 9). This folder contains a Ship CPP file (Main Source file), Ship H file (Header file), Ship DEF file (Definition file), Ship DSP file (Project file), Ship DSW file (Workspace file), StdAfx CPP file, and StdAfx H file. The Ship CPP file (Main Source file) can be seen in Appendix D, as mentioned previously. The other files are very similar to the corresponding files for the "Oscillator" example. While editing them, it is important to change the names of the source files with respect to the new file names. It is also important to make the required changes resulting from the new values of number of criteria, functional relations, and parameters. Notice that the Ship DSP file (Project file) and the Ship DSW file (Workspace file) can be edited as well using a simple text editor, although it is not recommended to do so.

Since the bulk carrier design optimization model did not have complicated calculations, it was simple to write it directly in Visual C++ to create the Dynamic Link Library. However, it would be easier to write more complex models in MATLAB, as the MOVI 1.3 software package is capable of optimizing the MATLAB models. This is why the bulk carrier design optimization model was first modified in MATLAB to start the

optimization process. At this time, the Dynamic Link Library (DLL) file was used to set up the "interface" between MOVI and MATLAB (See Figure 10).

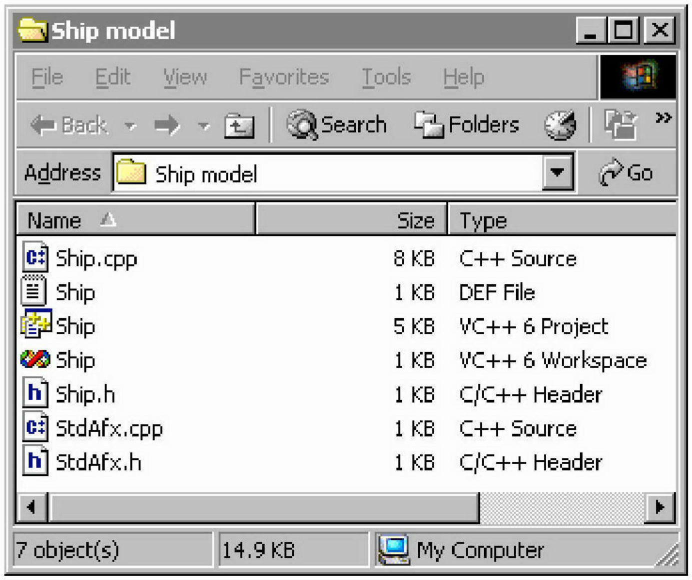

Figure 9 Visual C++ folder for the ship model.

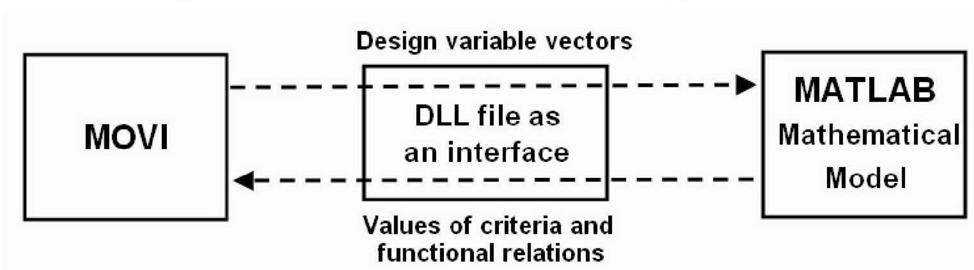

Figure 10 Data exchange between MOVI 1.3 and the MATLAB model via the DLL interface file (After Ref. [2].).

MOVI has Visual C++ files to create the Dynamic Link Library interface for the "Oscillator" example problem discussed in Reference [2] (MOVI\Examples\MatLab\Example_R13). Moreover, the Ship CPP file (Main Source file) for the bulk carrier design optimization model can be seen in Appendix C. This time the Ship CPP file does not have "computational code", since a MATLAB model will be used instead. In addition, the folder used for compiling contains three more files that were copied from the "MATLAB6p5\extern\include" folder (See Figure 11). These files are engine H file, matrix H file, and tmwtypes H file. Also, before compiling the interface, the Ship DSP file lines 136, 140, and 144 must be fixed to designate the correct paths to MATLAB libraries called libmat.lib, libmx.lib, and libeng.lib. For example:

136 SOURCE=c:\Matlab6p5\extern\lib\win32\microsoft\msvc60\libmat.lib

140 SOURCE=c:\Matlab6p5\extern\lib\win32\microsoft\msvc60\libmx.lib

144 SOURCE=c:\Matlab6p5\extern\lib\win32\microsoft\msvc60\libeng.lib

would be the correct paths if the libraries were in the "c:\Matlab6p5\extern\lib\win32 \microsoft\msvc60" folder.

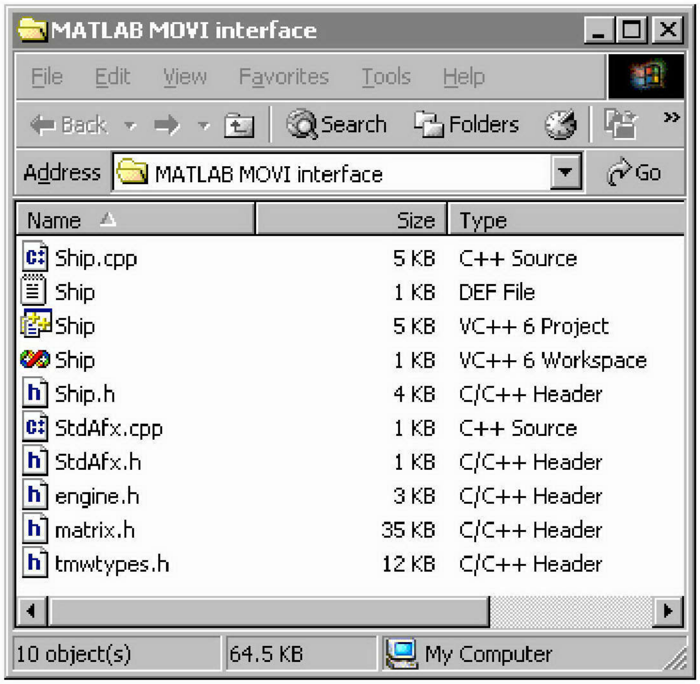

Figure 11 Visual C++ folder for the MATLAB-MOVI interface.

Once the Dynamic Link Library interface is generated, MOVI can begin optimization. Notice that the MATLAB model file should be in the path "C:\MATLAB6p5\work" before starting the optimization process. There are seven main menu buttons in MOVI. These are "Data input", "Check of Primary Constraints", "Test Table", "Tables", "Histograms and Graphs", "Perform One Test", and "Combine Solutions". There is a "New Task" option under the "Data Input" menu that can be used to develop new task folders. The desired name and path of the new task folder should be entered into the "New Task" dialog box (See Figure 12). In fact, MOVI automatically creates new folders under the "MOVI\Problems" folder unless another path is entered. The path of the Dynamic Link Library interface should also be an input in order to attach

the library to the task folder. After attaching the library, the new path becomes the new task folder and the DLL parameters can be seen in the dialog box (See Figure 13).

It is possible, but not required, to edit the design variables, functional constraints, and criteria using the new menus that appear in the "New Task" dialog box once the library is attached (See Figure 13). At that time, it is also possible, but not mandatory, to put in the "Number Generator" type and "Size of the Test Portion". All these inputs can be done during the task editing process which will be discussed later in this chapter.

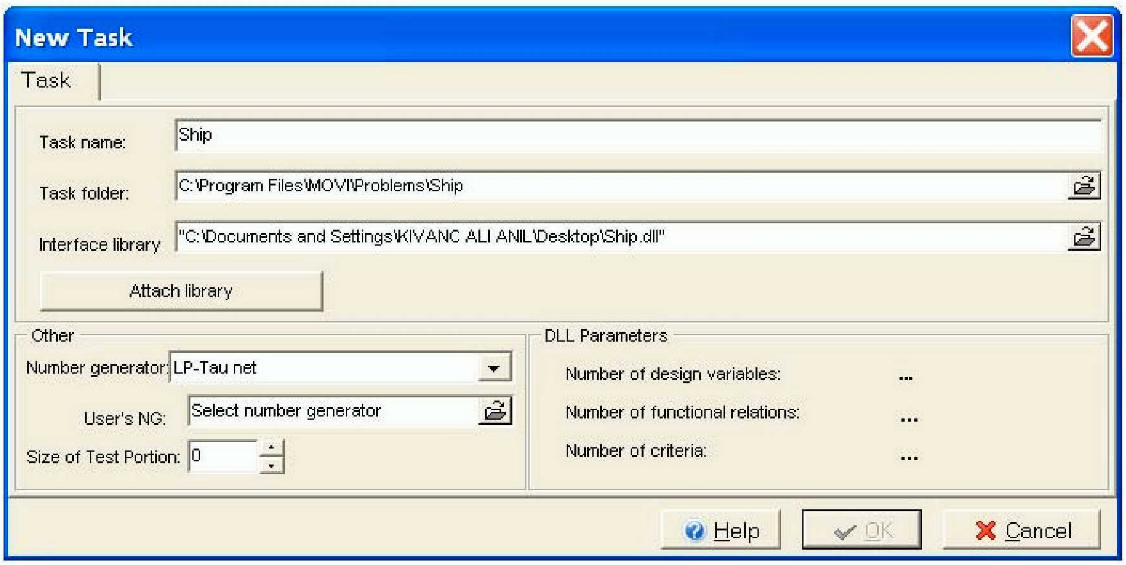

Figure 12 Data Input (New Task) Dialog Box.

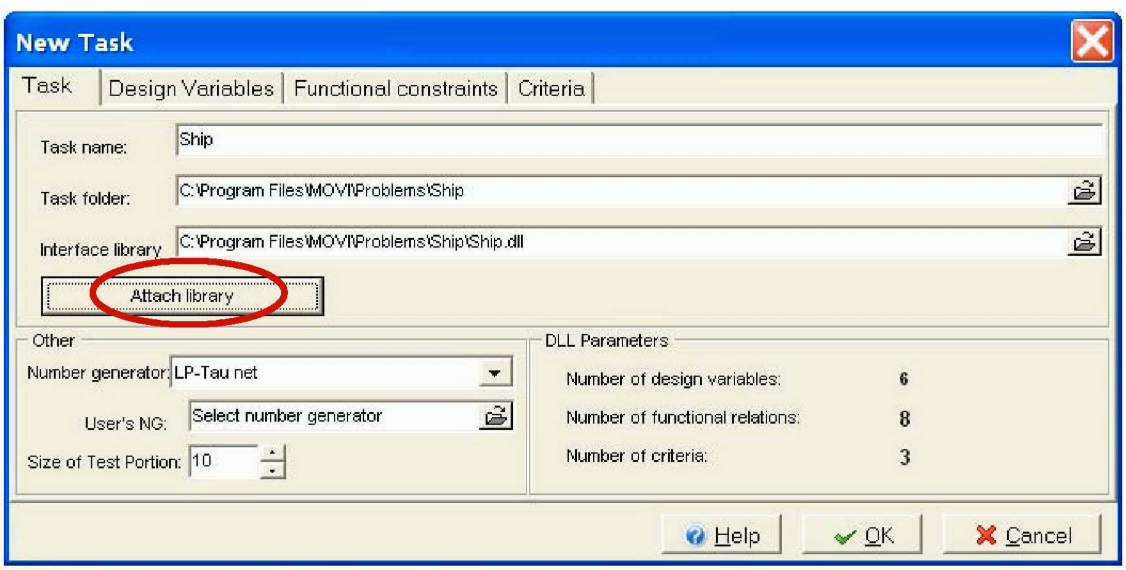

Figure 13 Data Input (Attach Library).

The new task folder includes the Ship.dll (Dynamic Link Library interface file), Ship TSK file (Task Project file), and base file (InterBase Database file) (See Figure 14). There are also two example task folders, "Oscillator" and "Oscillator1", under the "MOVI\Problems" folder provided with MOVI software. Task Project files can be loaded anytime using the "Load Task" option under the "Data Input" menu (Figure 15).

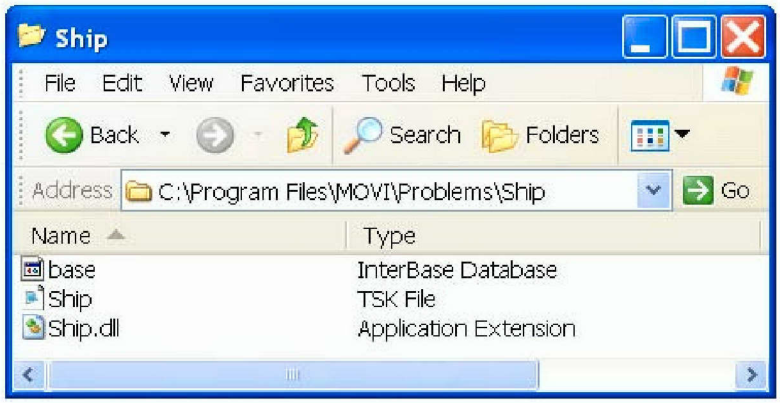

Figure 14   New Task Folder.

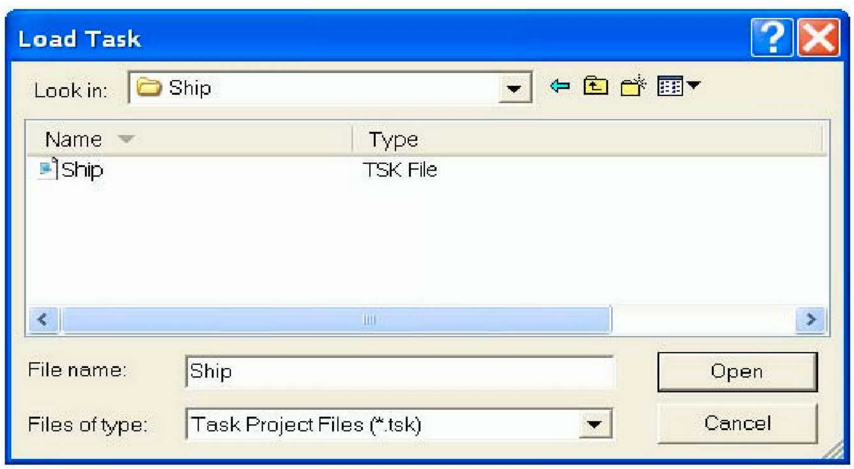

Figure 15   Data Input (Load Task).

Task editing is the second step after the new task folder is created. The "Edit Task" option is also under the "Data Input" menu. If the "Number Generator" type and "Size of the Test Portion" were not entered during the "New Task" process, they can be edited using the "Task Editing" dialog box (See Figure 16). There are three options for the "number generator". These are LP Tau (generator of uniformly distributed sequences), Windows RNG and User NG. LP Tau is the default generator and, when it is used, the number of variables shouldn't go above fifty-one. Windows RNG is an MS

Windows built-in Random Number Generator. There is virtually no limit to the number of parameters when this generator is used. User NG is a user-supplied number generator. Connecting these user-supplied number generators is explained in detail in Appendix A of Reference [2]. The default generator, LP Tau, was selected for the bulk carrier design optimization model. The default value for "Size of Test Portion" is 10. It specifies a number of tests that will be saved to the disk right away throughout the optimization process. [2]

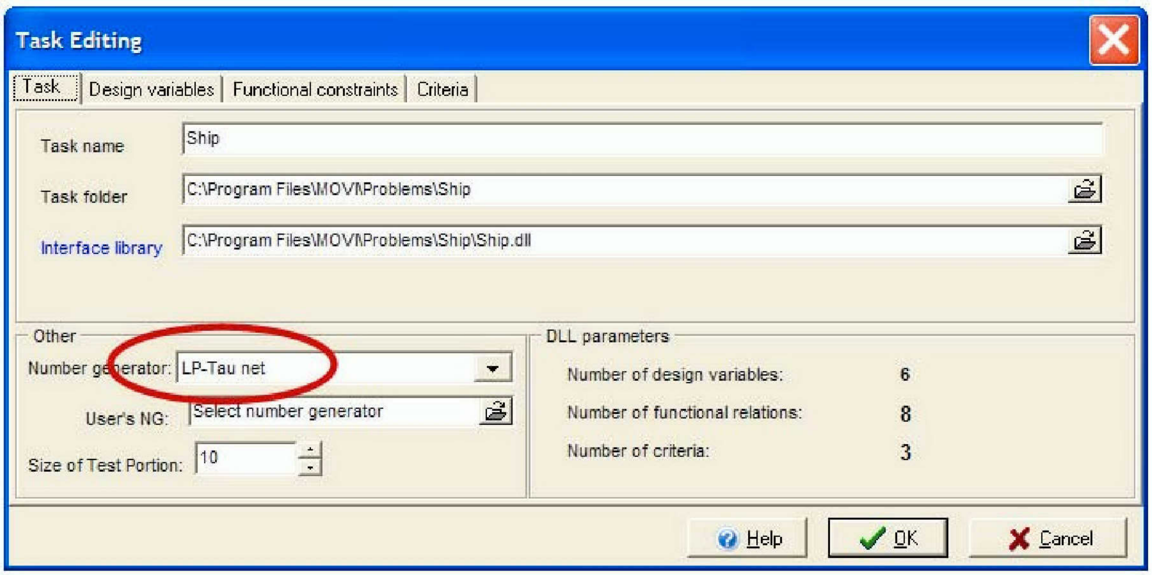

Figure 16 Task Editing Dialog Box.

The design variables, functional constraints, and criteria that were not revised during the "New Task" process can be edited as well using the "Task Editing" dialog box. The names, types, and lower and upper bounds of the design variables should be entered first (See Figure 17). The default type for design variables is "Continuous" unless the "Discrete" check box is selected. The preferred values for discrete variables can be an input using the "List of values" button under the "Discrete" check box. For instance, "number of main propulsion engines" might be a discrete variable. There was no discrete variable for the bulk carrier design optimization model. The upper bound of the length (L), the lower and upper bounds of the block coefficient (C_B), and speed (V_k) were given, as mentioned before. Referring to the results in Reference [5] (See Table 6),

reasonable values were selected for the other design variable constraints. These initial constraints were improved during the optimization process, which will be discussed later in this chapter.

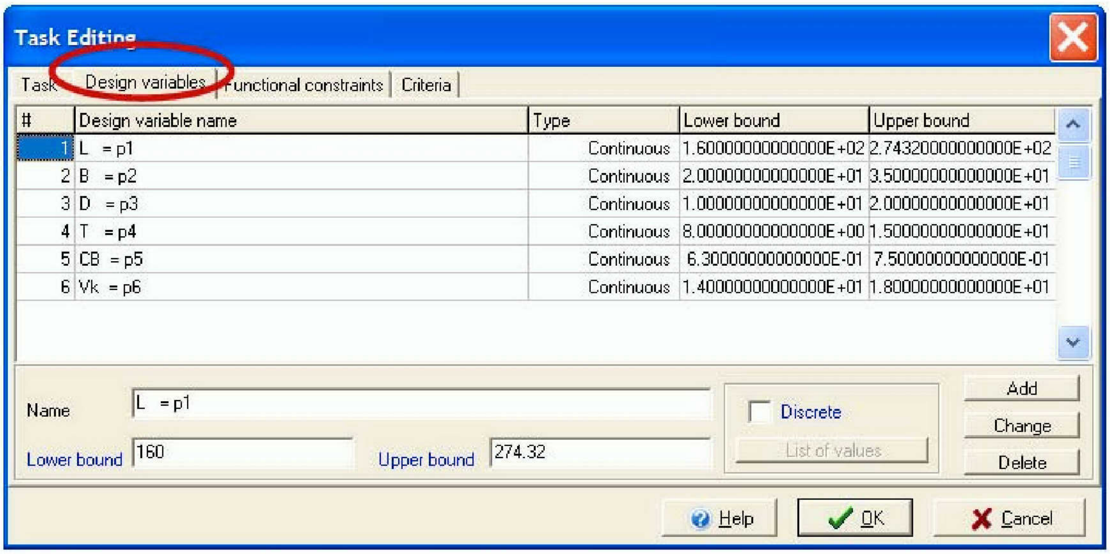

Figure 17 Task Editing (Design Variables) Dialog Box.

After editing the design variables, the “Functional relation name”, “DLL function name”, and the comparison type and constraint value for each functional constraint should be introduced (See Figure 18). There were eight functional relations subject to nine functional constraints for the bulk carrier design optimization model.

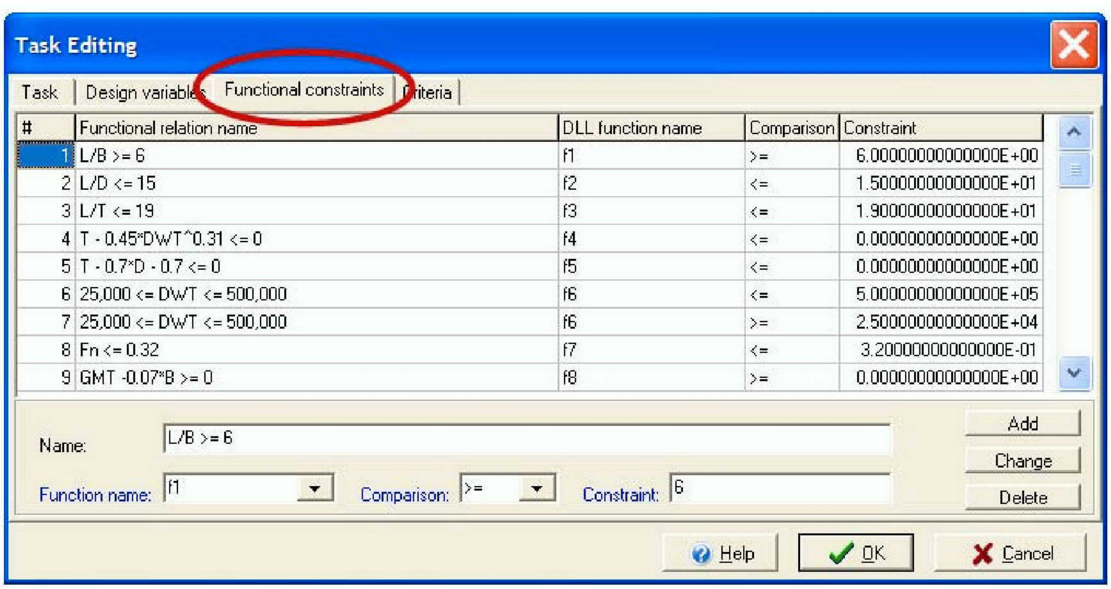

Figure 18 Task Editing (Functional Constraints) Dialog Box.

Finally, using the criteria page of the "Task Editing" dialog box, criteria can be edited (See Figure 19). The "Criterion name", "DLL function name", and the optimization type (MIN/MAX) should be an input for this process. The default type for criterion is "Criterion" unless the "Pseudocriterion" check box is selected. It is not required to input constraint values if there are no primary constraints for the criteria. The primary constraints can be entered after selecting the "Constraint" check box for the corresponding criteria. There were no pseudo-criteria or primary criteria constraints for the bulk carrier design optimization model.

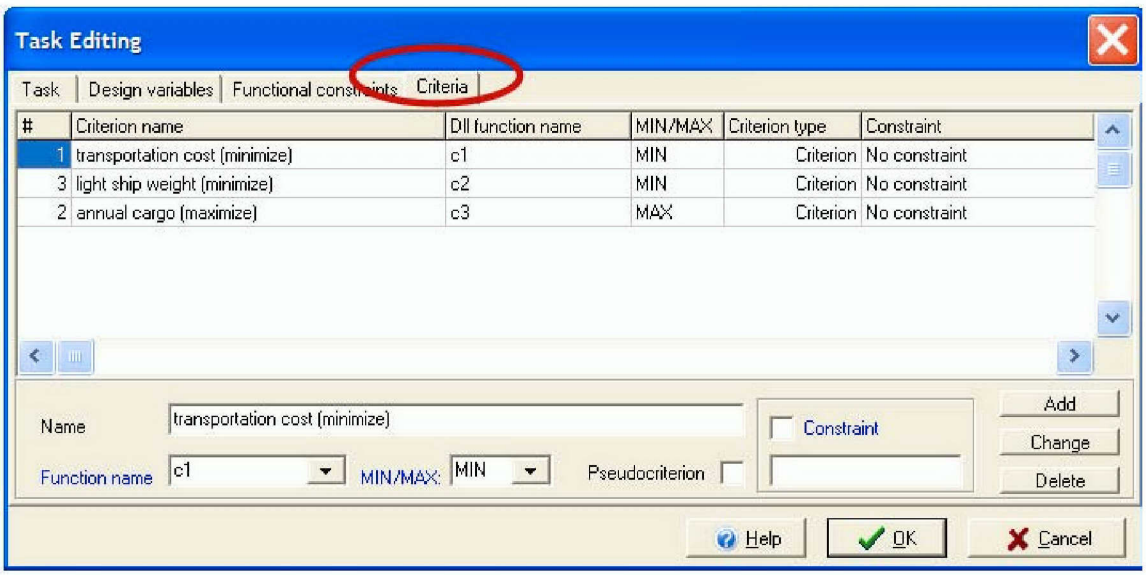

Figure 19 Task Editing (Criteria) Dialog Box.

The "Check of Primary Constraints" dialog box is used to start performing tests for optimization (See Figure 20). Test ranges should be integers. It is better to perform 2^n number of tests if the default number generator LP Tau was selected. This menu provides the opportunity to divide the desired number of tests into pieces. For example, to perform 8,192 (2^{13}) tests, test ranges can be from 1 to 4,096 (2^{12}), and from 4,097 to 8,192. Therefore, two different computers can be used at the same time. The test range can be divided more to use more computers. The "Combine Solutions" menu is used to unite the separated results. This procedure saves a lot of time when the required number of tests is very large. The "Check of Primary Constraints" dialog box also displays the information about the results (See Figure 20). For the bulk carrier design optimization model, 8,192 tests were performed, which means 8,192 "design variable vectors" were generated by

MOVI and sent to the mathematical model. After the computations, 8,065 of them did not satisfy the functional constraints and only 127 design variable vectors entered the test table. Since there were no primary criteria constraints, the total number of criteria failures is zero.

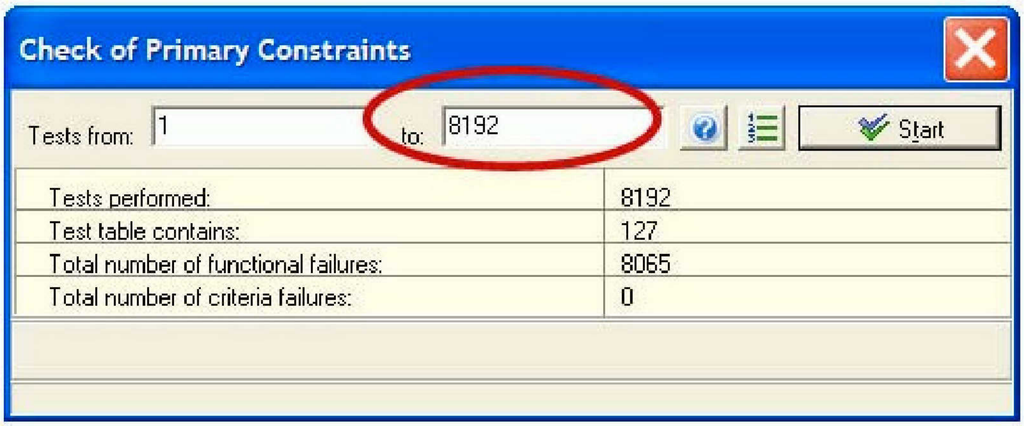

Figure 20 Check of Primary Constraints Dialog Box.

The "Test Table" menu is used to begin the analysis of the results with the "Full Ordered Test Table" (See Figure 21). The values of criteria are displayed in order from best to worst. For instance, if the criterion is minimized, the test table presents the values in increasing order. The corresponding "design variable vector" numbers for each criterion value are also included. It is first required to determine the criteria constraints by selecting the worst desired value for each criterion. Tolerating one of the criteria constraints leads to more vectors in the table. Therefore, the designer must do a trade-off analysis among the criteria. This process can be repeated to construct the best feasible set. After determination of criteria constraints, the truncated table of feasible solutions can be generated using the "Truncated Table" button (See Figure 22). Moreover, feasible and Pareto optimal sets can be constructed using the "Results" button. The feasible and Pareto optimal solutions for the bulk carrier design optimization model are presented in Figure 23. After 8,192 tests and determination of criteria constraints, the truncated table contains 25 vectors, the feasible set contains 25 vectors, and the Pareto optimal set has 16 vectors. Each vector represents a possible design for this model.

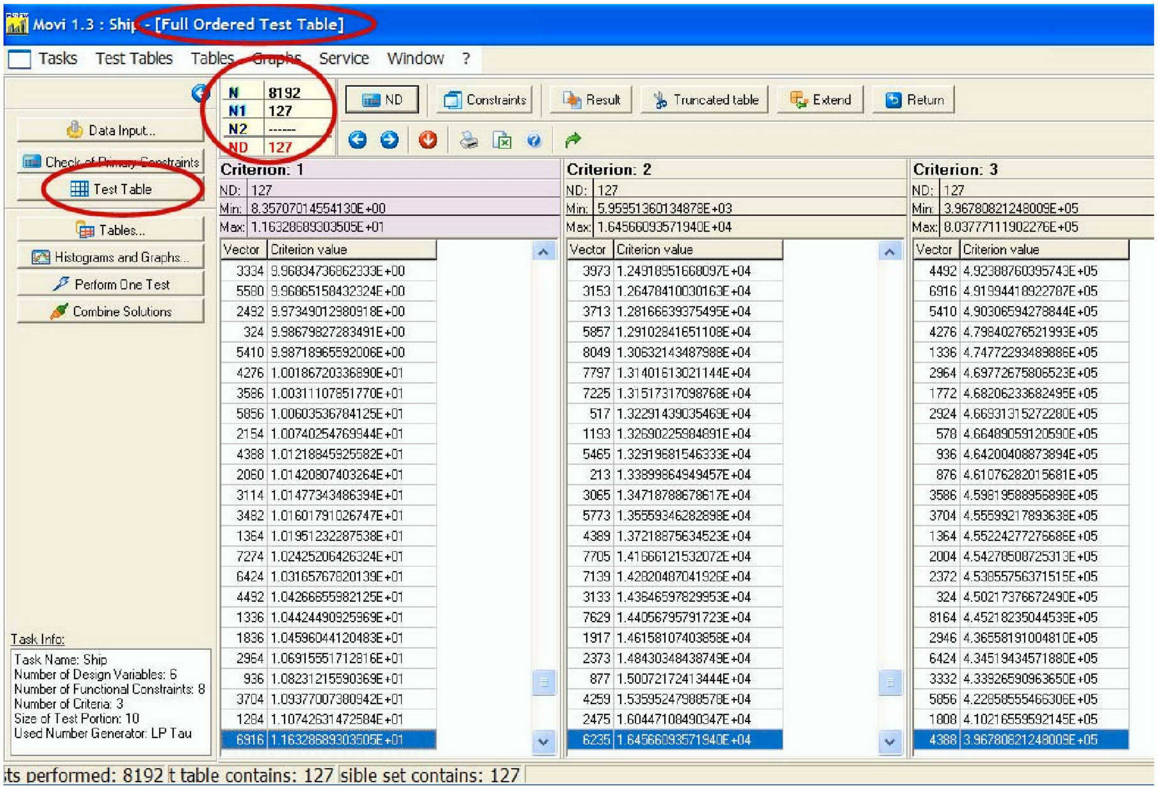

Figure 21 Full Ordered Test Table.

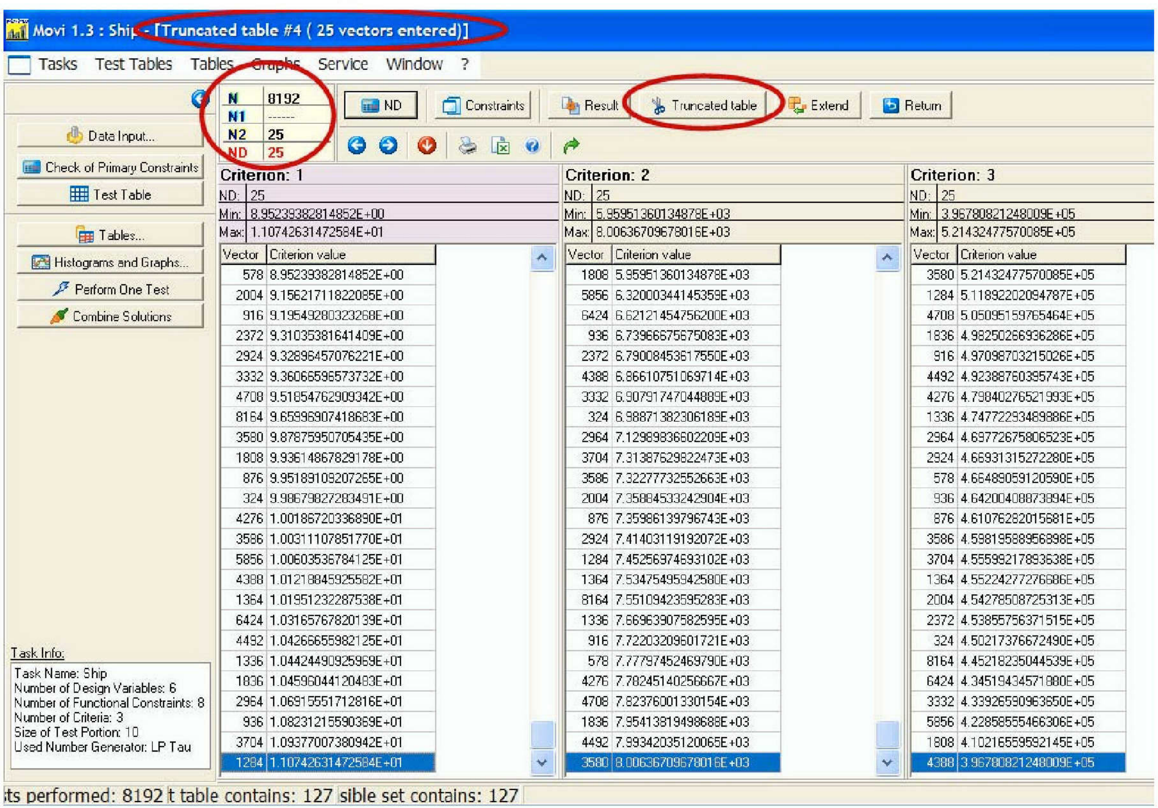

Figure 22 Truncated Table.

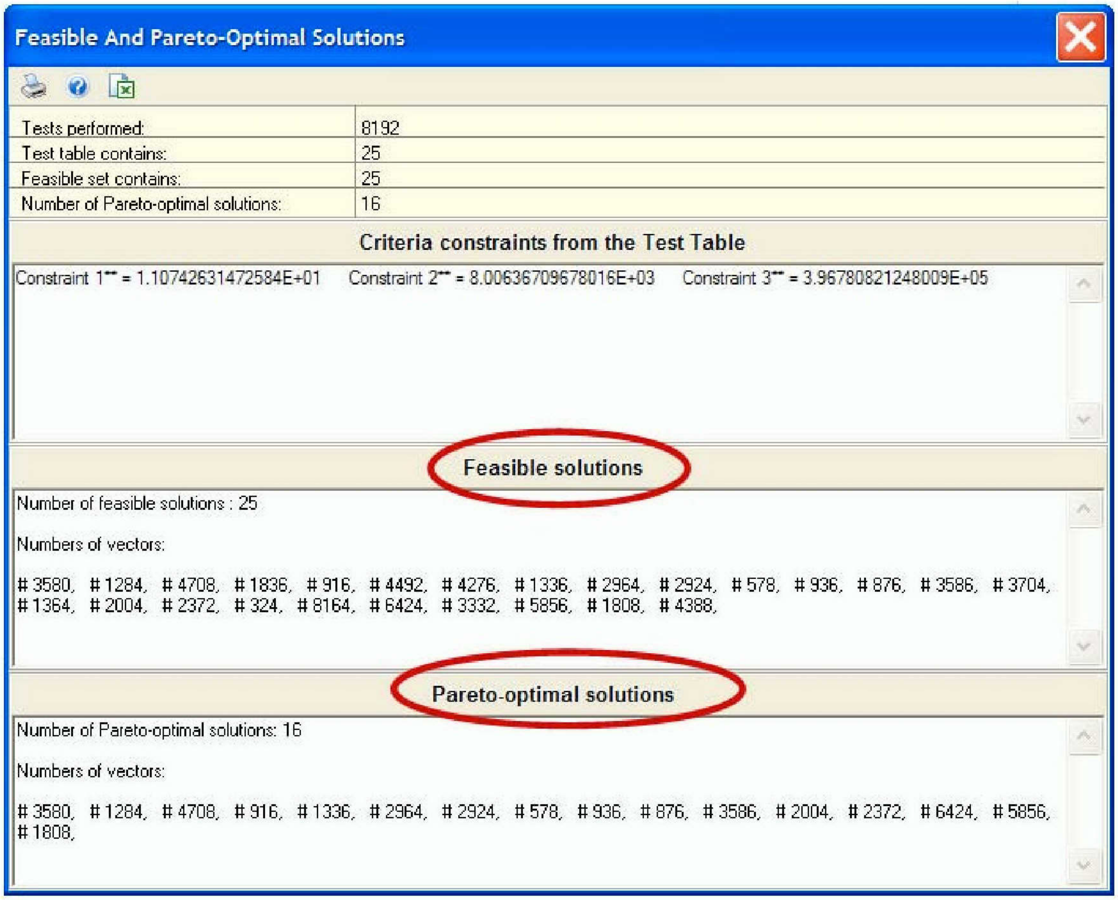

Figure 23 Feasible and Pareto Optimal Solutions.

Analysis of these results is very essential for improvement. There are several ways to investigate the optimization results with MOVI. There is a "Table of Criteria" option under the "Tables" menu that can be used to see the criteria values (See Figure 24). There is also a "Table of Designs" option that can be used to observe the design variable values (See Figure 25). The vectors in the feasible and Pareto optimal sets or all of the vectors by numbers can be examined utilizing these options. Furthermore, the "Table of Functional Failures" and "Table of Criteria Failures" selections are available under the "Tables" menu. These are used to scrutinize the functional and criteria constraints respectively. If needed, functional and criteria constraints can be corrected using the "Table of Functional Failures" and "Table of Criteria Failures". Correction can be a complete change or simply a relaxation of constraints to improve the results. An example of the relaxation of a functional constraint will be discussed later in this chapter.

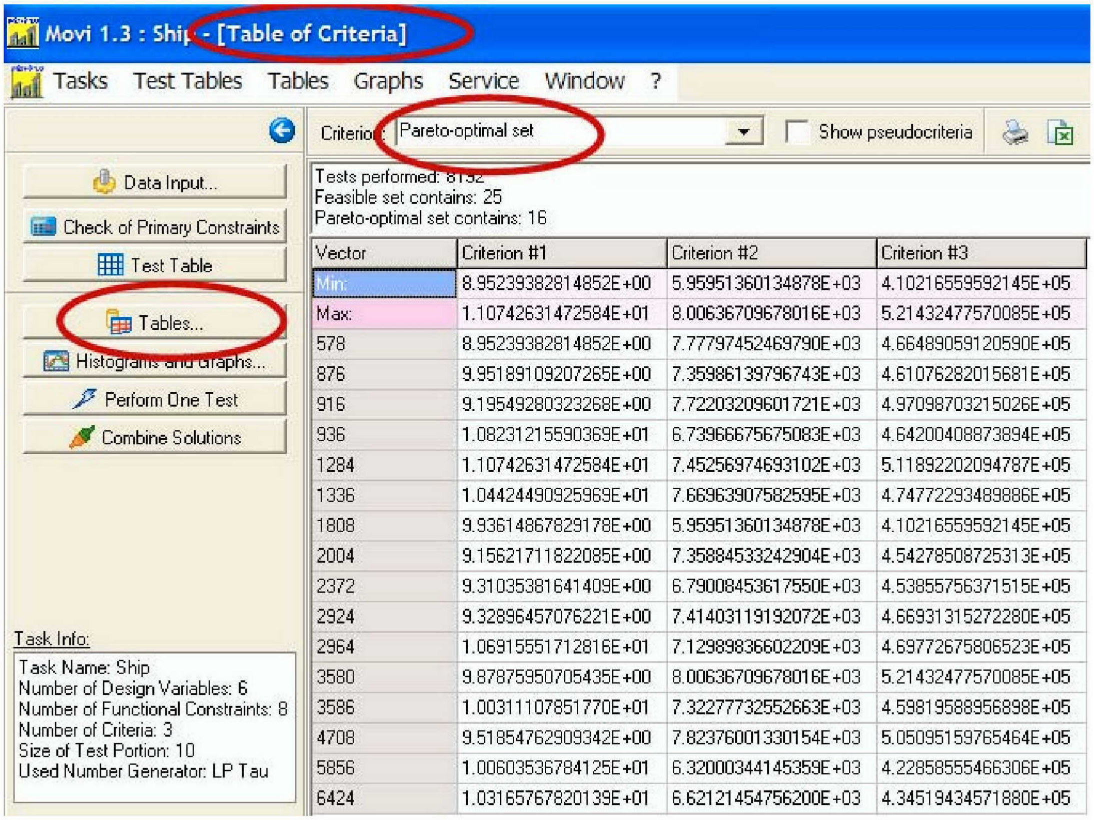

Figure 24 Table of Criteria (Pareto Optimal Set).

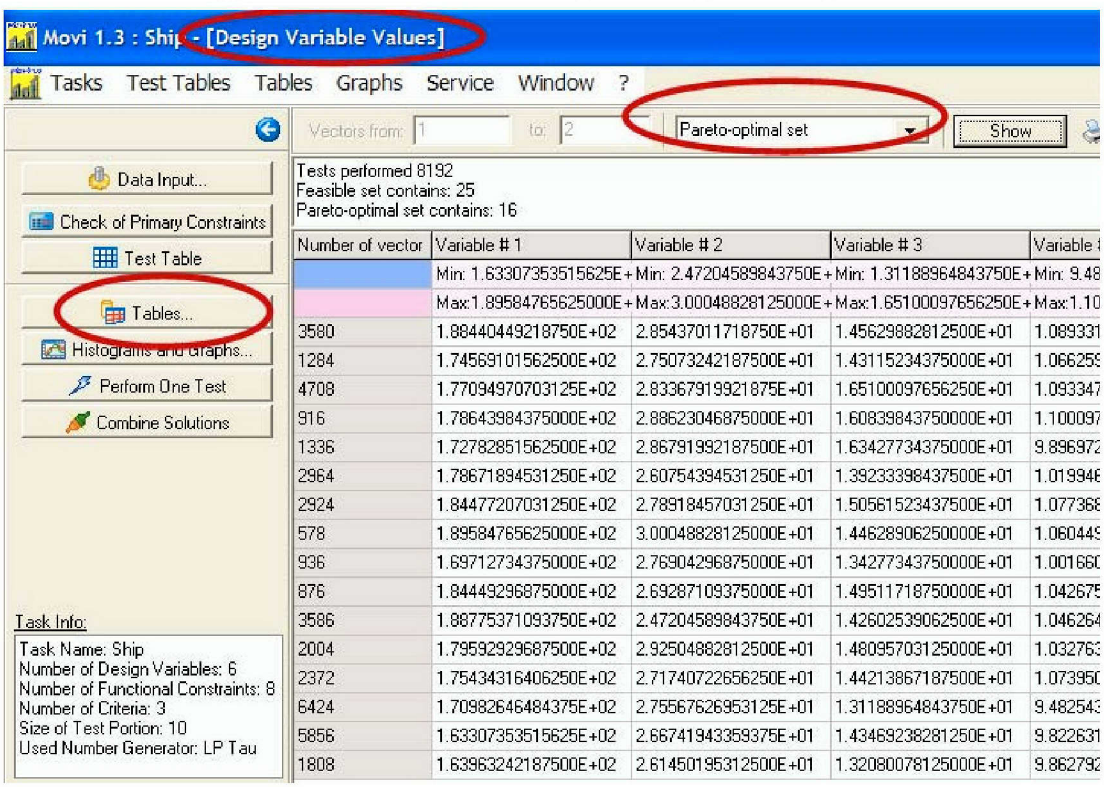

Figure 25 Table of Designs (Pareto Optimal Set).

The design variable histograms are used to monitor the distribution of the design variables for the feasible set between the lower and upper bounds. This feature of MOVI gives the opportunity to correct the parameter boundaries that were selected previously. For the bulk carrier design optimization model, an analysis of the design variable (feasible set) histograms was conducted. It was observed that the first four variables were lumped within their ranges, whereas the last two variables were more evenly distributed (See Figure 27 – Figure 32). Therefore, the upper bound for the "Design Variable 1" was redefined, although it was given that "$L <= 274.32$ m" is an initial constraint in the problem statement. Additionally, the lower and upper boundaries of the "Design Variable 2", "Design Variable 3", and "Design Variable 4" were reevaluated.

Using the "Task Editing" dialog box, the corrected bounds for design variables were entered to start the second optimization run (See Figure 26). Note that the criteria constraints that were applied during the first optimization must be deleted in order to get the "Full Ordered Test Table" for the next optimization run. This can be done using the "Task Editing" dialog box as well. For the second optimization process, again 8,192 tests were conducted. As a result, 7,188 solutions did not satisfy the functional constraints, and 1,004 vectors entered the "Full Ordered Test Table". After analysis of the test table and determination of criteria constraints, 188 vectors entered the truncated table. The feasible set had 188 vectors and the Pareto optimal set had 39 vectors.

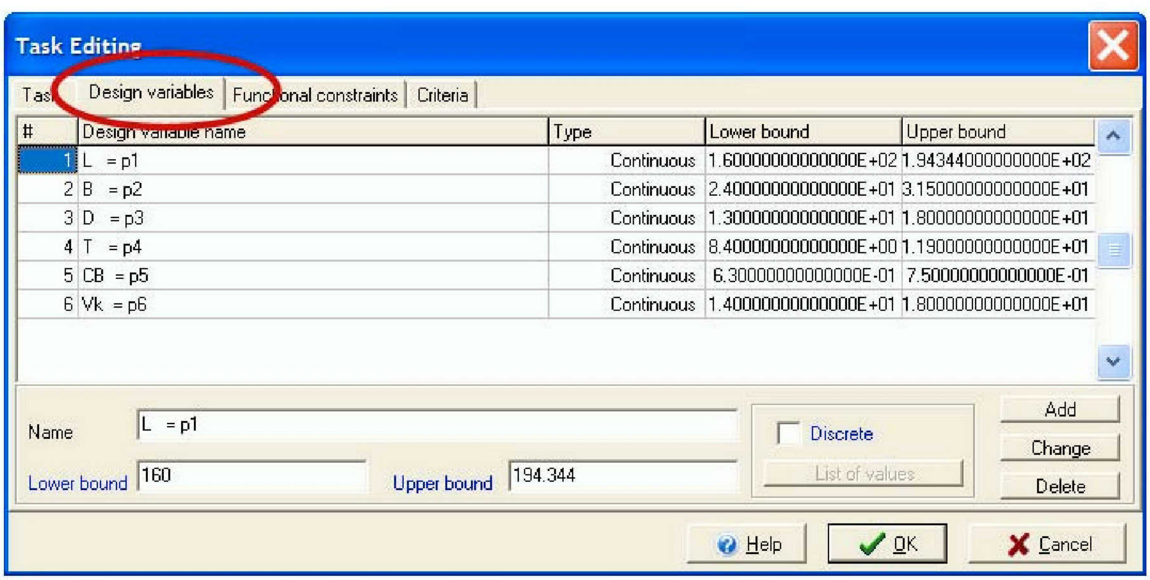

Figure 26 Corrected Bounds for Design Variables.

The analysis of the design variable (feasible set) histograms shows that the distribution of variables within their ranges was improved after this second optimization (See Figure 33 – Figure 38). However, the lower and upper bounds of variables can still be restructured to achieve more uniform distributions. Since the results were satisfactory, another optimization run was not conducted. Note that, instead of the histograms, the minimum and maximum values presented in the "Table of Designs" can be used to analyze the allocation of the feasible design variables within their bounds. On the other hand, the feasible set histograms offer an opportunity for visual inspection, which is more convenient.

It was possible to improve the results utilizing the "Table of Functional Failures" option, as mentioned earlier. The number of functional failures with respect to each functional constraint can be seen and corrected in this table. Correction can be a complete change or simply a relaxation of constraints. For example, if the functional constraint "$L/B \geq 6$" were relaxed to be "$L/B \geq 5.999$" for the bulk carrier design optimization model, five more vectors would enter the feasible set (See Figure 39). Actually, instead of using the "Table of Functional Failures", it is better to accept the functional relations that have flexible constraints as pseudo-criteria at the beginning of the optimization process. In this way, the desired values of functional constraints can be agreed upon during the determination of criteria constraints with the "Full Ordered Test Table". The "Table of Criteria Failures" option can be used in the same way as the "Table of Functional Failures" if the primary criteria constraints were applied at the beginning of the optimization process.

The dependency of criteria on design variables for Pareto optimal vectors can be examined using the "Criterion versus Design Variable I" graphs. These graphs ensure improvement of the Pareto optimal solutions. Examples of these graphs that show the relationship between the criteria and "Design Variable 1" for one of the Pareto optimal vectors (Vector # 4118) were obtained after the second optimization run for the bulk carrier design optimization model (See Figure 40 – Figure 42). The first criterion was contradictory with the second and third criteria for the first design variable, which can be observed from these graphs.

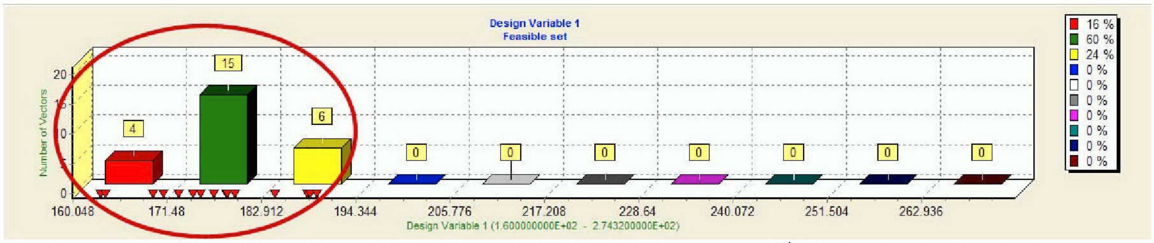

Figure 27 Design Variable 1, Feasible Set Histogram, 1st Opt. (Bulk Carrier).

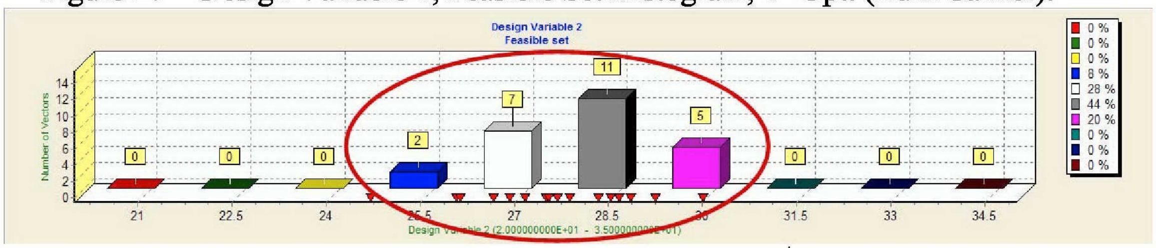

Figure 28 Design Variable 2, Feasible Set Histogram, 1st Opt. (Bulk Carrier).

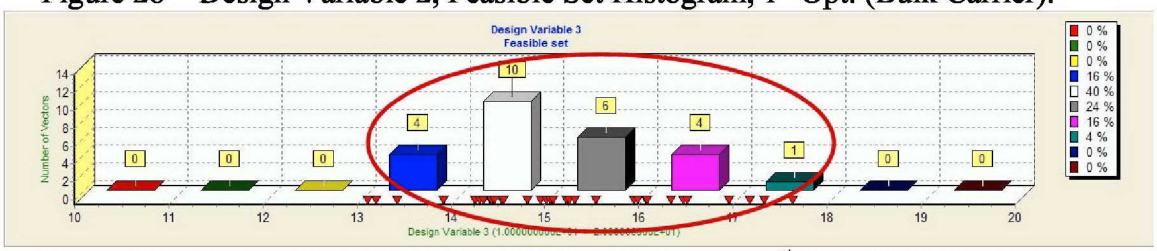

Figure 29 Design Variable 3, Feasible Set Histogram, 1st Opt. (Bulk Carrier).

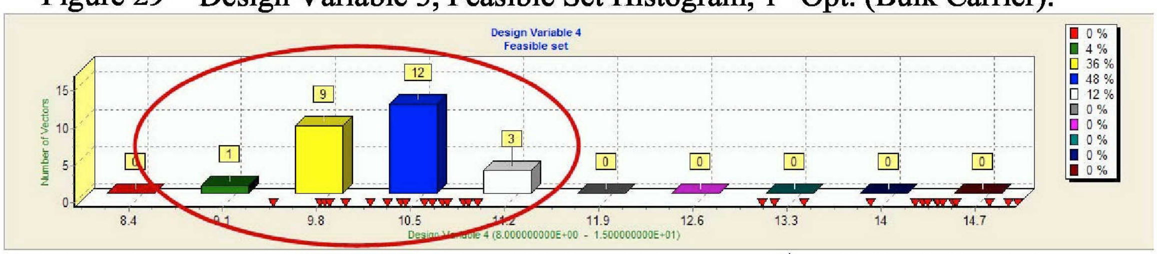

Figure 30 Design Variable 4, Feasible Set Histogram, 1st Opt. (Bulk Carrier).

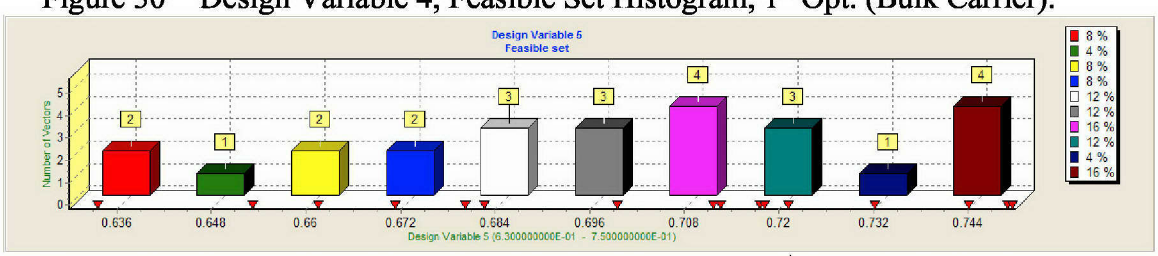

Figure 31 Design Variable 5, Feasible Set Histogram, 1st Opt. (Bulk Carrier).

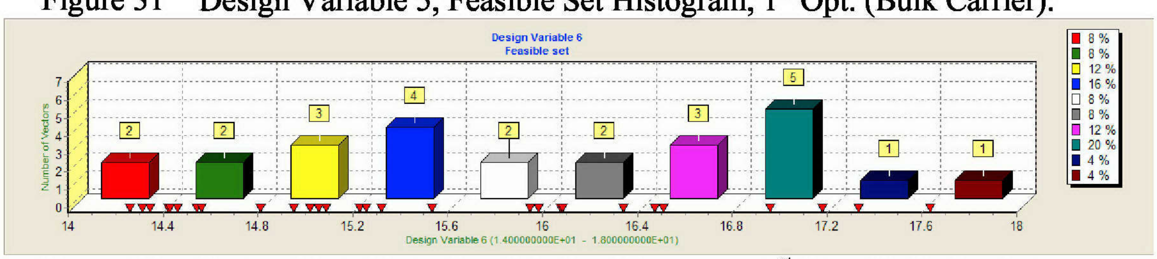

Figure 32 Design Variable 6, Feasible Set Histogram, 1st Opt. (Bulk Carrier).

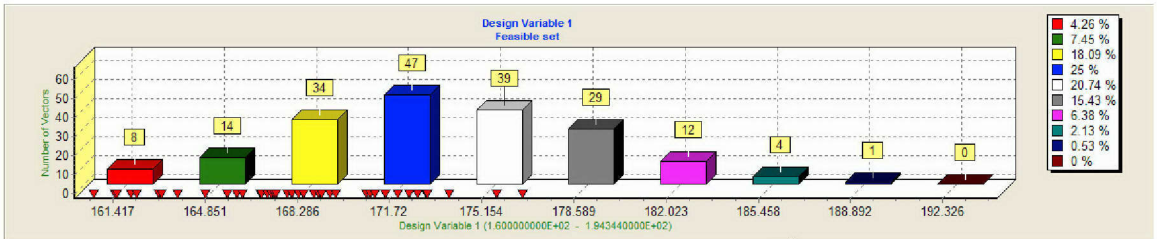

Figure 33 Design Variable 1, Feasible Set Histogram, 2nd Opt. (Bulk Carrier).

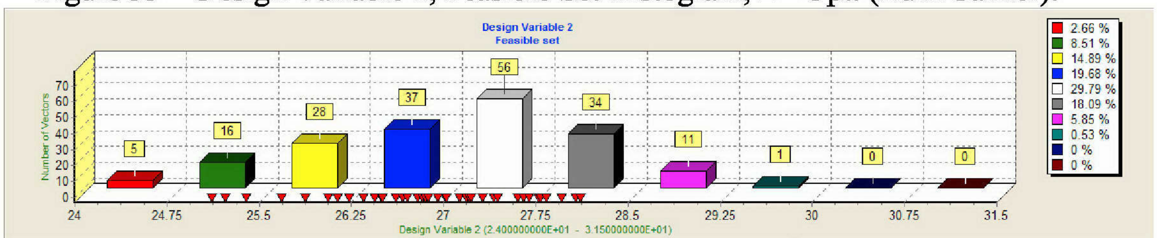

Figure 34 Design Variable 2, Feasible Set Histogram, 2nd Opt. (Bulk Carrier).

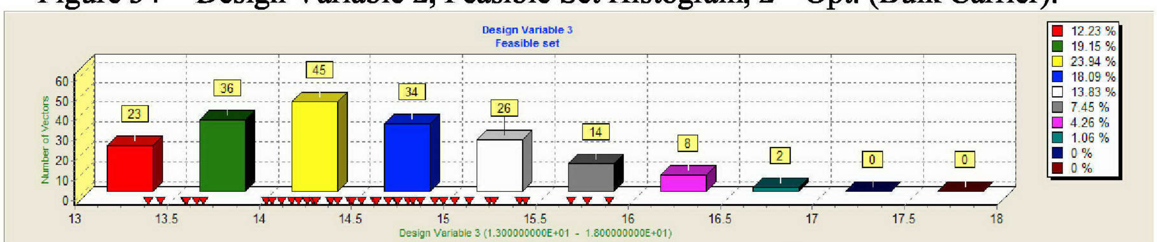

Figure 35 Design Variable 3, Feasible Set Histogram, 2nd Opt. (Bulk Carrier).

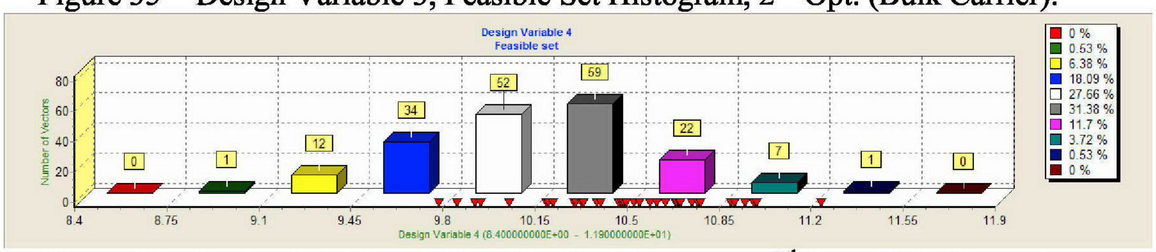

Figure 36 Design Variable 4, Feasible Set Histogram, 2nd Opt. (Bulk Carrier).

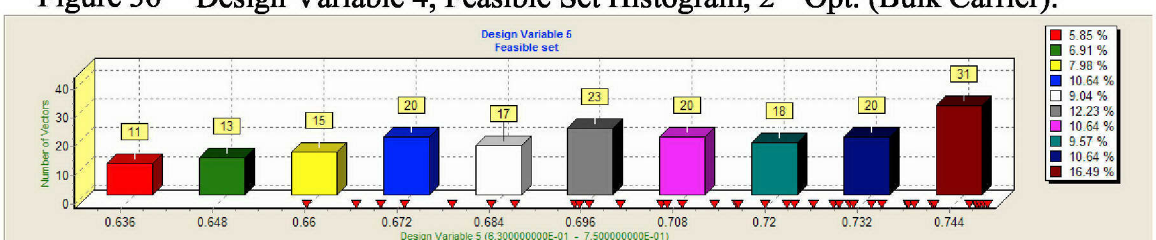

Figure 37 Design Variable 5, Feasible Set Histogram, 2nd Opt. (Bulk Carrier).

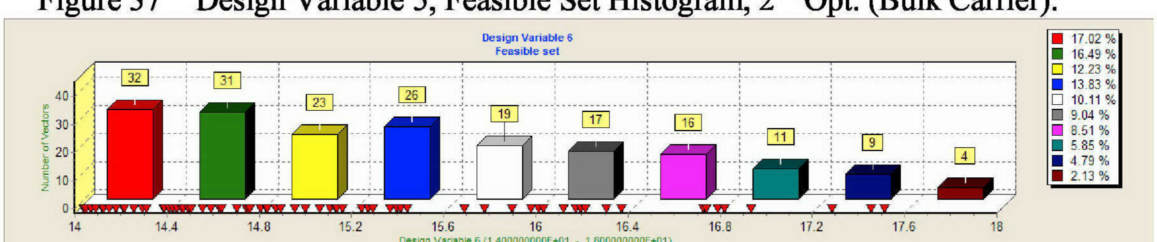

Figure 38 Design Variable 6, Feasible Set Histogram, 2nd Opt. (Bulk Carrier).

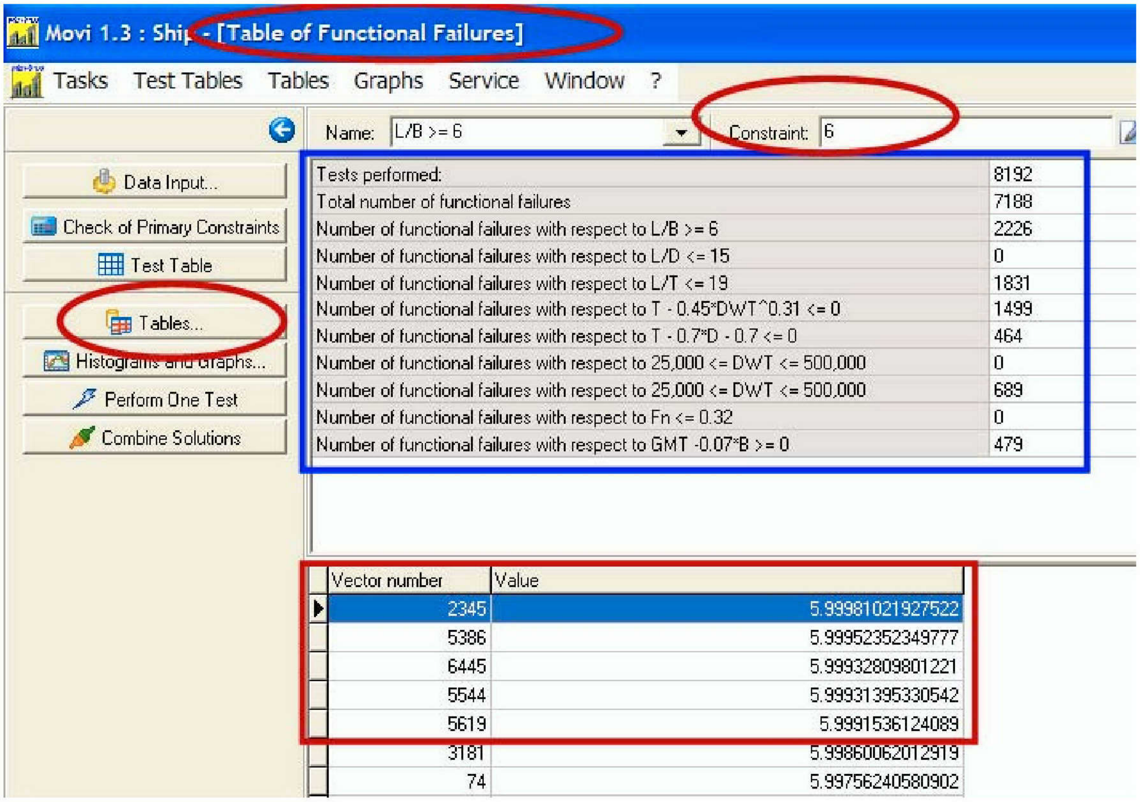

Figure 39 Table of Functional Failures.

The dependency of criteria on design variables for the entire vector set can be analyzed simultaneously using the "Criterion versus Design Variable II" graphs. Examples of these graphs for "Design Variable 1" are presented for the bulk carrier design optimization model (See Figure 43 – Figure 45). The contradictory behavior of the first criterion with the second and third criteria can also be observed from these graphs for the first design variable.

The "Criterion versus Criterion" graphs of MOVI provide an opportunity for visual inspection of the dependency of criteria on other criteria (See Figure 46 – Figure 48). For example, the "Criterion 2" (Light Ship Weight) was minimized, and the "Criterion 3" (Annual Cargo) was maximized. These two criteria were obviously in contradiction, as mentioned earlier. This contradiction can be seen in Figure 48. The magenta-colored, diamond-shaped points represent the infeasible solutions. The blue-colored, square-shaped points represent the feasible solutions. Finally, the green-colored points represent the Pareto optimal solutions.

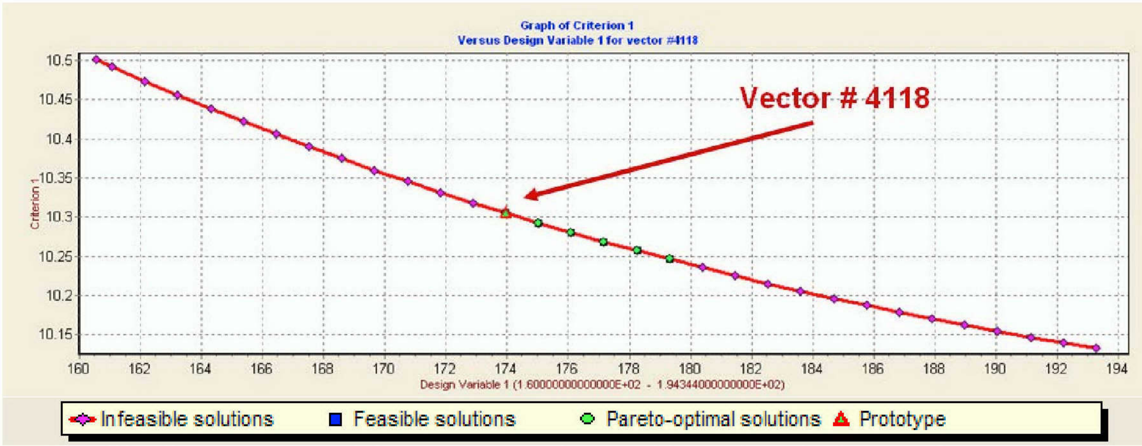

Figure 40 The Dependency of Criterion 1 on Design Variable 1 for Pareto Optimal Solution # 4118, 2nd Optimization (Bulk Carrier).

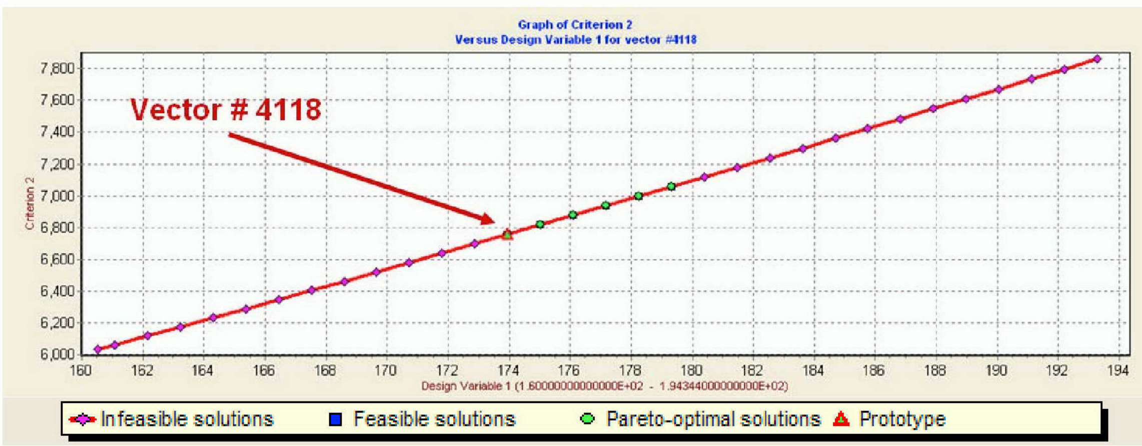

Figure 41 The Dependency of Criterion 2 on Design Variable 1 for Pareto Optimal Solution # 4118, 2nd Optimization (Bulk Carrier).

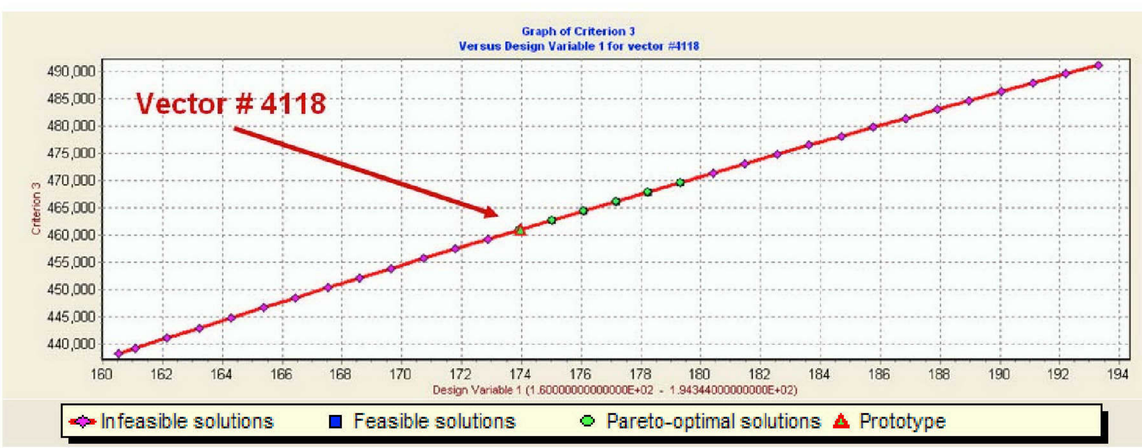

Figure 42 The Dependency of Criterion 3 on Design Variable 1 for Pareto Optimal Solution # 4118, 2nd Optimization (Bulk Carrier).

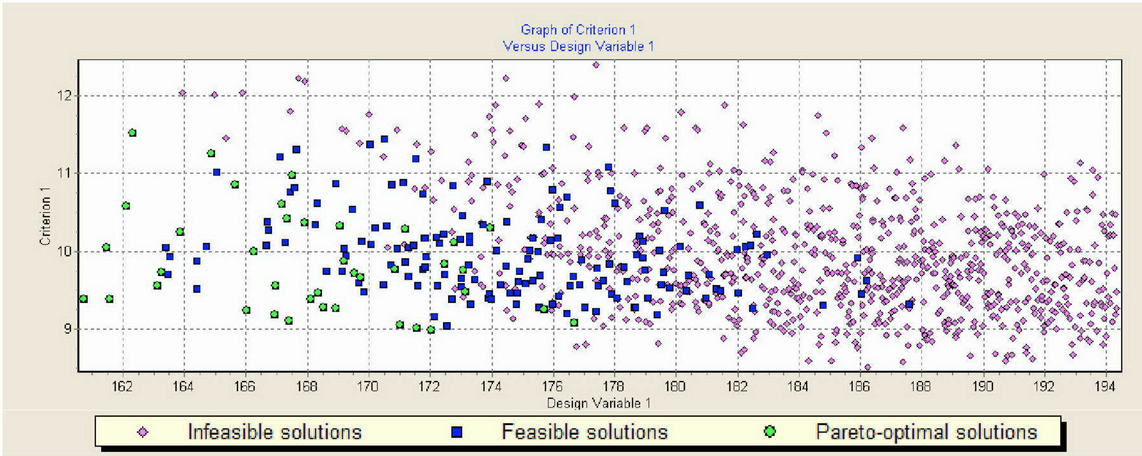

Figure 43 The Dependency of Criterion 1 on Design Variable 1, 2nd Opt.

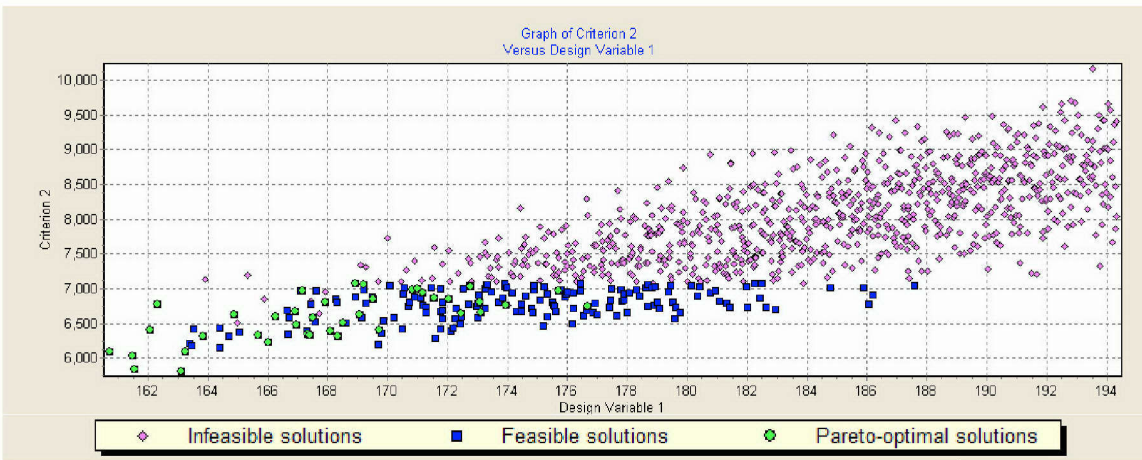

Figure 44 The Dependency of Criterion 2 on Design Variable 1, 2nd Opt.

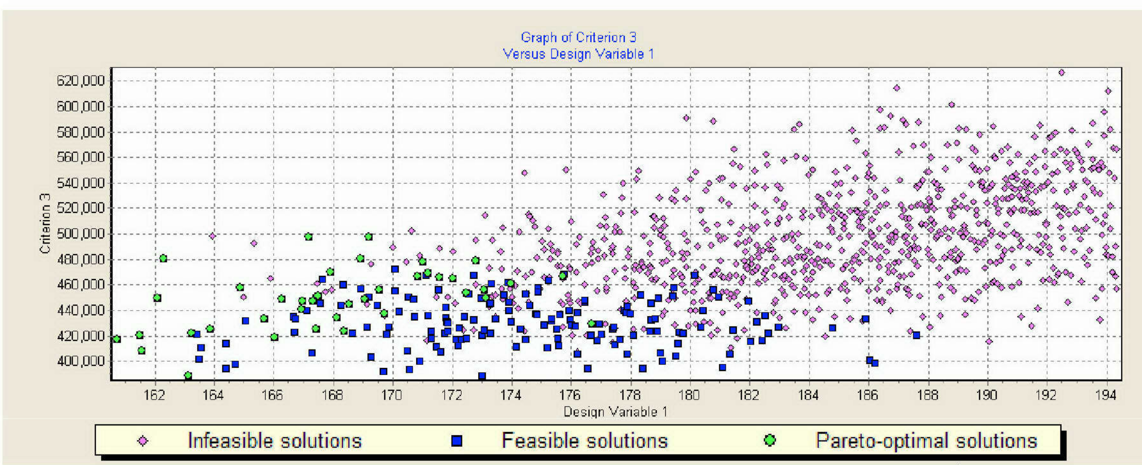

Figure 45 The Dependency of Criterion 3 on Design Variable 1, 2nd Opt.

D. SUMMARY OF RESULTS

In this study, a basic commercial ship design optimization model for bulk carriers was investigated using the Parameter Space Investigation (PSI) technique. The model was modified for MOVI 1.3 software to understand, demonstrate, and validate the features of it step-by-step. The review of criterion and variable definitions for the modified model can be seen in Table 4. Two optimization runs were conducted. After the second optimization run the feasible set had 188 vectors and the Pareto optimal set had 39 vectors. The values of criteria and design variables for the vectors in the Pareto optimal set are presented in Table 5. The model has been previously analyzed using many optimization methods such as "weighted sum", "minimum-maximum", "weighted minimum maximum", "goal programming", and "nearest to the utopian design" methods. The results of those optimization methods are shown in Table 6. Comparison of these tables reveals that the results obtained by the Parameter Space Investigation technique are consistent with the earlier results of mentioned methods. The similarities of the "Criterion versus Criterion" graphs and the projections of the Pareto surface graphs which were taken from the Reference [5], provide evidence to this consistency (See Figure 46 – Figure 51). Utilizing the fact that there were three criteria, three dimensional criterion graphs were plotted in MATLAB to observe the Pareto set more efficiently (See Figure 52 & Figure 53). Since the results were satisfactory, another optimization run was not conducted, but the options of MOVI software for analyzing and improving the results were demonstrated.

Criterion #1	**transportation cost (£/t)**
Criterion #2	**light ship weight (t)**
Criterion #3	**annual cargo (t)**
Variable # 1	**length (m) L**
Variable # 2	**beam (m) B**
Variable # 3	**depth (m) D**
Variable # 4	**draft (m) T**
Variable # 5	**block coefficient C_B**
Variable # 6	**speed (knots) V_k**

Table 4 The Review of Criterion and Variable Definitions for the Bulk Carrier Design Optimization Model.

Tests performed 8192
Feasible set contains: 146
Pareto-optimal set contains: 39

	# of vector	Criterion #1	Criterion #2	Criterion #3	Variable # 1	Variable # 2	Variable # 3	Variable # 4	Variable # 5	Variable # 6
1	226	9.716	6,850.201	456,667.225	169.525	26.607	15.441	10.546	0.748	15.109
2	290	9.879	7,053.307	497,836.591	169.190	28.116	14.807	10.909	0.730	16.195
3	1396	9.999	6,595.151	448,699.343	166.255	27.226	15.273	10.470	0.701	15.979
4	1434	8.991	6,857.799	465,302.255	172.024	27.021	14.746	10.948	0.749	14.150
5	1596	9.385	6,385.747	434,211.463	168.100	27.409	13.598	10.200	0.717	14.701
6	1696	9.388	6,092.592	417,649.865	160.721	26.443	15.063	10.487	0.734	14.217
7	2028	10.973	6,588.573	451,560.426	167.496	25.227	14.702	10.384	0.742	16.740
8	2122	9.063	7,004.999	478,456.093	171.009	27.133	15.689	11.239	0.747	14.470
9	2412	10.419	6,353.191	447,361.550	167.320	26.064	14.039	10.481	0.696	16.790
10	2508	9.192	6,674.035	440,565.528	166.917	27.441	15.777	10.686	0.726	14.118
11	2544	10.585	6,407.315	449,989.819	162.088	26.855	14.293	10.194	0.739	16.306
12	2596	11.248	6,634.859	457,687.349	164.872	26.701	14.874	10.327	0.706	17.513
13	2762	10.283	6,941.009	469,163.925	171.177	26.496	15.245	10.614	0.724	16.372
14	2826	9.779	6,983.067	467,127.089	170.842	27.770	14.630	10.306	0.739	15.442
15	2950	9.485	6,659.746	449,692.978	173.122	25.397	14.493	10.703	0.748	14.833
16	3208	11.514	6,775.663	480,260.359	162.306	26.792	14.998	10.646	0.742	17.456
17	3304	9.558	5,811.754	389,281.878	163.111	25.679	13.397	9.853	0.732	14.050
18	3322	10.112	7,030.911	478,717.811	172.770	27.320	14.178	10.400	0.735	16.175
19	3384	10.249	6,317.658	425,346.986	163.849	26.953	14.832	10.052	0.697	16.011
20	3932	10.370	6,803.807	470,215.857	167.907	26.873	15.413	10.746	0.707	16.726
21	4118	10.305	6,756.733	461,030.318	173.956	26.828	14.424	10.588	0.660	17.286
22	4304	10.051	6,037.302	420,241.556	161.480	26.506	13.662	9.945	0.731	15.395
23	4370	9.666	6,406.107	438,001.225	169.731	25.876	14.258	10.526	0.716	15.293
24	4604	9.289	6,516.606	444,965.250	168.523	26.140	15.137	10.896	0.729	14.590
25	4844	9.106	6,333.252	425,740.630	167.416	27.788	14.751	10.701	0.667	14.461
26	5144	9.731	6,087.257	421,903.012	163.241	26.348	14.212	10.299	0.713	15.163
27	5226	9.014	6,867.039	465,880.176	171.558	27.696	14.954	10.983	0.720	14.444
28	5294	9.264	6,968.857	467,052.253	175.717	28.077	14.505	10.778	0.679	15.366
29	5698	9.277	7,074.518	480,937.191	168.909	27.835	15.896	10.993	0.749	14.760
30	6092	9.556	6,484.338	447,577.425	166.964	27.205	13.699	10.220	0.748	14.893
31	6594	10.335	6,621.257	449,088.708	169.068	27.222	13.602	9.921	0.723	16.216
32	6608	9.384	5,836.636	408,006.455	161.555	25.112	14.071	10.467	0.749	14.091
33	6718	9.082	6,753.588	429,399.994	176.681	27.185	14.389	10.546	0.684	14.041
34	6970	9.835	6,644.216	453,834.958	172.456	26.233	14.555	10.690	0.695	16.033
35	7252	10.854	6,328.252	433,516.212	165.664	26.661	13.463	9.786	0.709	16.820
36	7292	9.463	6,317.147	423,913.539	168.347	27.013	14.635	10.496	0.670	15.132
37	7814	9.759	6,801.131	456,191.395	173.076	27.958	14.308	10.384	0.673	16.121
38	7852	10.609	6,963.664	497,673.935	167.173	27.606	14.386	10.767	0.739	16.933
39	7988	9.240	6,226.486	419,298.601	166.033	27.650	14.122	10.336	0.687	14.410
	Min	**8.991**	**5,811.754**	**389,281.878**	**160.721**	**25.112**	**13.397**	**9.786**	**0.660**	**14.041**
	Max	**11.514**	**7,074.518**	**497,836.591**	**176.681**	**28.116**	**15.896**	**11.239**	**0.749**	**17.513**

Table 5 MOVI 1.3 Results (Pareto Optimal Set) for the Bulk Carrier Design Optimization Model.

OPTIMIZATION METHOD	Criterion #1	Criterion #2	Criterion #3	Variable # 1	Variable # 2	Variable # 3	Variable # 4	Variable # 5	Variable # 6
Weighted Sum Design ($w_1=w_2=w_3$)	9.474	5,240.300	386,500.000	150.730	25.120	13.840	10.390	0.750	14.000
Min - Max Design	11.514	7,709.600	549,557.000	169.070	28.180	15.360	11.450	0.750	18.000
Nearest to the Utopian Design	8.953	6,290.900	452,018.000	161.960	26.990	14.870	11.110	0.750	14.050
Weighted Sum Design ($w_1=w_3=0.4$, $w_2=0.2$)	8.742	6,808.000	480,947.000	167.120	27.850	15.350	11.440	0.750	14.000
Weighted Sum Design ($w_2=w_3=0.2$, $w_1=0.6$)	8.814	6,566.500	462,985.000	165.690	27.620	15.060	11.240	0.736	14.000
Weighted Sum Design ($w_1=w_2=0.2$, $w_3=0.6$)	8.626	7,179.500	501,210.000	170.640	28.440	15.670	11.670	0.750	14.000
Weighted min-max ($w_2=w_3=0.6$, $w_1=1.8$)	9.281	7,379.300	527,783.000	170.720	28.450	15.630	11.640	0.750	15.500
Weighted min-max ($w_1=w_3=0.6$, $w_2=1.8$)	9.116	6,274.400	424,010.000	168.840	28.100	14.190	10.630	0.643	14.790
Weighted min-max ($w_1=w_2=0.6$, $w_3=1.8$)	10.332	10,529.900	689,587.000	192.340	32.060	17.490	12.950	0.750	18.000
Goal Programming ($w_1=w_2=w_3=1/3$)	9.474	5,240.300	386,500.000	150.730	25.120	13.840	10.390	0.750	14.000
Goal Programming ($w_1=0.6$, $w_2=w_3=0.2$)	8.826	6,535.200	461,666.000	165.290	27.550	15.040	11.230	0.738	14.000
Goal Programming ($w_1=w_2=0.2$, $w_3=0.6$)	8.626	7,179.500	501,209.000	170.640	28.440	15.670	11.670	0.750	14.000

Table 6 The Results of Other Optimization Methods (After Ref. [5].).

Result validation was ensured with a Microsoft Excel spreadsheet version of the bulk carrier design optimization model, which uses the same algorithm. First, the Microsoft Excel spreadsheet model was tested and approved with the values from Table 6. Then, using the "Perform One Test" menu, values of the selected design variable vector and corresponding values of functional relations and criteria were exported to Microsoft Excel. Using this data, the Microsoft Excel test of the results was performed. Repeating this test for different vectors demonstrated that there were no or negligible floating point errors. An example of this test is presented in Appendix E.

The main purpose of this study was to demonstrate and validate the features of the Parameter Space Investigation (PSI) approach. This bulk carrier design optimization model was selected due to its relatively small dimensionality and the availability of existing studies. After validation of the results, this study was used as a template for a more realistic example. The example was based on the "MIT Functional Ship Design Synthesis Model" with a greater number of parameters, criteria, and functional constraints, which will be discussed in the next chapter.

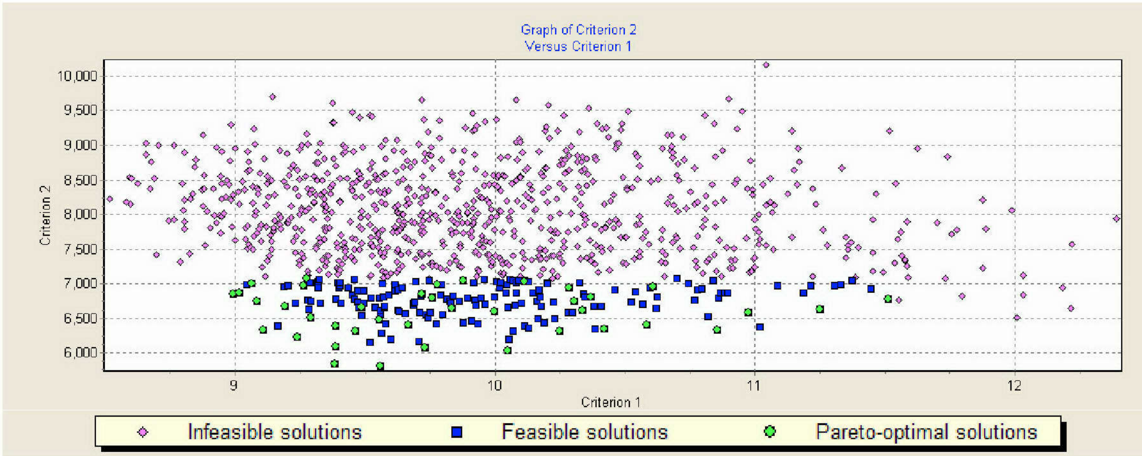

Figure 46 Criterion 1 Transport Cost (Min) vs. Criterion 2 Light Ship Weight (Min).

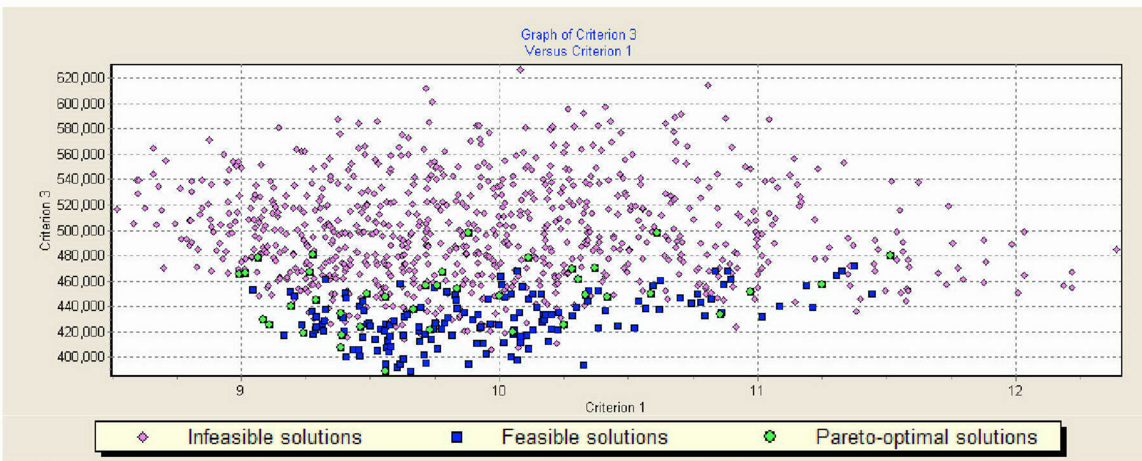

Figure 47 Criterion 1 Transport Cost (Min) vs. Criterion 3 Annual Cargo (Max).

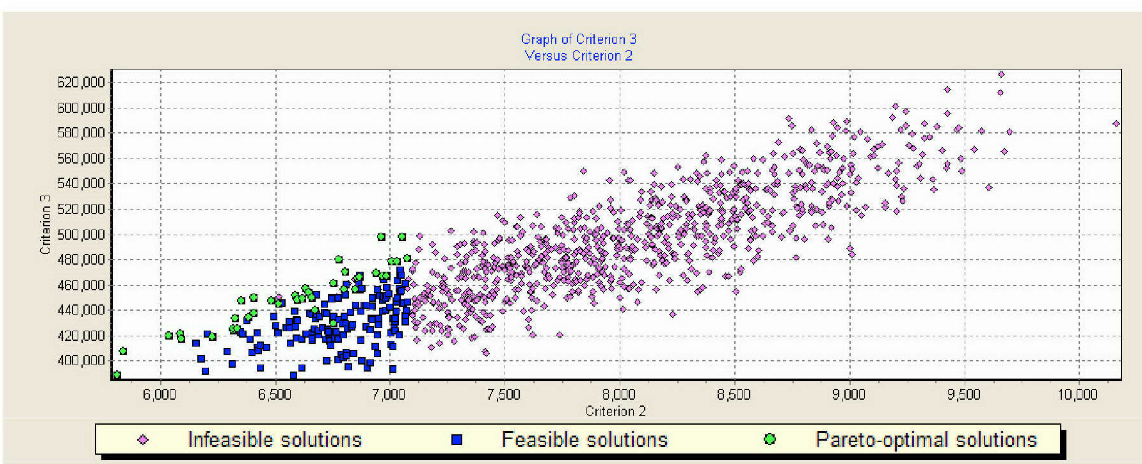

Figure 48 Criterion 2 Light Ship Weight (Min) vs. Criterion 3 Annual Cargo (Max).

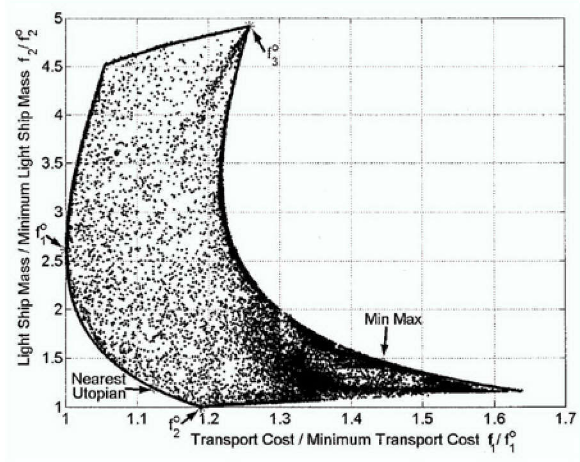

Figure 49 Criterion 1 Transport Cost (Min) vs. Criterion 2 Light Ship Weight (Min) Projection of Pareto Surface (From Ref. [5].).

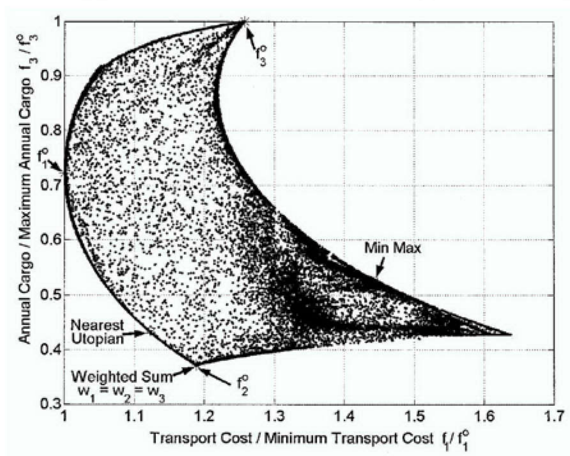

Figure 50 Criterion 1 Transport Cost (Min) vs. Criterion 3 Annual Cargo (Max) Projection of Pareto Surface (From Ref. [5].).

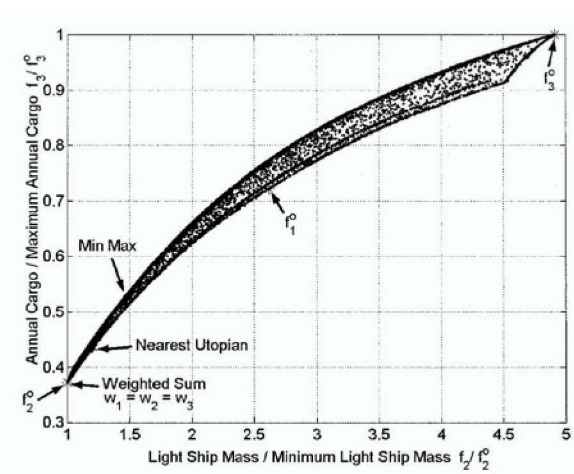

Figure 51 Criterion 2 Light Ship Weight (Min) vs. Criterion 3 Annual Cargo (Max) Projection of Pareto Surface (From Ref. [5].).

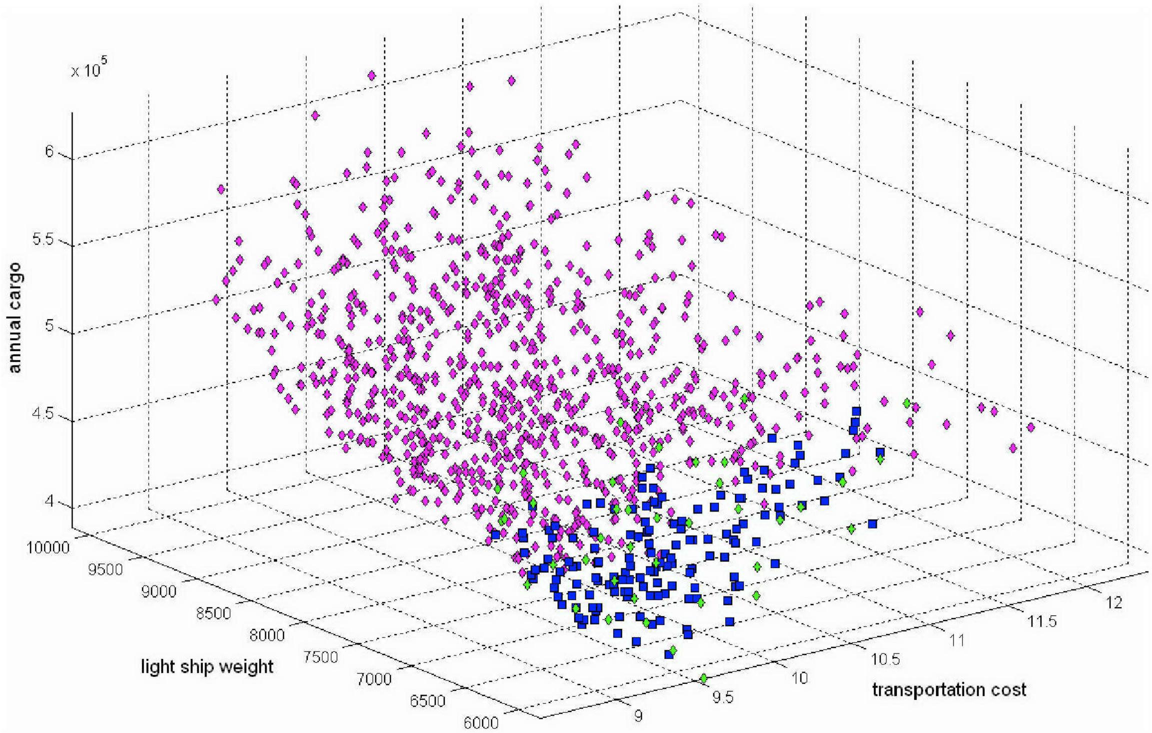

Figure 52 3D MATLAB Plot of Criterion 1 Transportation Cost (Min) vs. Criterion 2 Light Ship Weight (Min) vs. Criterion 3 Annual Cargo (Max).

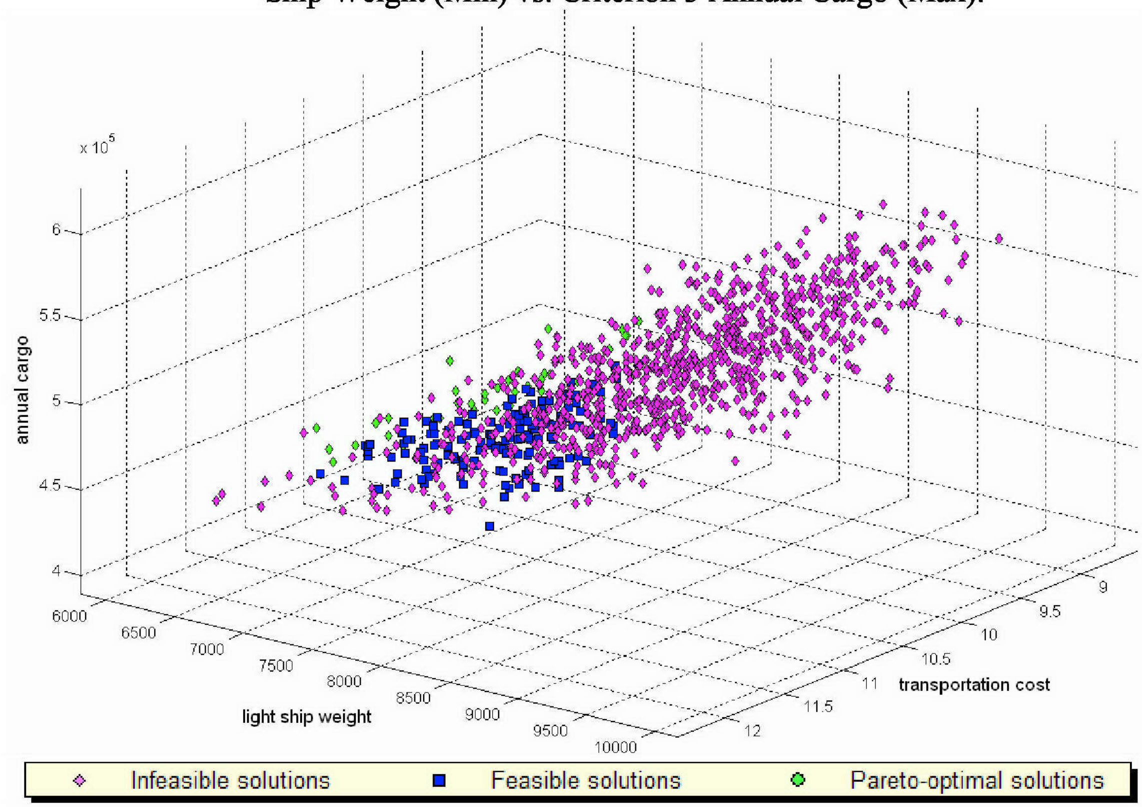

Figure 53 3D MATLAB Plot of Criterion 1 Transportation Cost (Min) vs. Criterion 2 Light Ship Weight (Min) vs. Criterion 3 Annual Cargo (Max).

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IV. MULTI-CRITERIA ANALYSIS OF MIT FUNCTIONAL SHIP DESIGN SYNTHESIS MODEL

A. INTRODUCTION

The Naval Ship design optimization example is the adapted MATLAB version of the "MIT Functional Ship Design Synthesis Model", which was previously written in Mathcad programming language. It was a modified version of the "Axiomatic Design Model" created by John Szatkowski in 2000. Essentially, the MIT Functional Ship Design Synthesis Model is a concept-level design mathematical model of monohull surface combatants that is used in the "13.412 Principles of Naval Ship Design" course offered at the Massachusetts Institute of Technology. The model originated as a master thesis by M. R. Reed in 1976 and has been modified by naval officer students and faculty of MIT for more than twenty years. Two earlier codes, the Navy's destroyer design model, DD07, and the "Center of Naval Analyses Conceptual Design of Ships Model (CODESHIP)", are used as its basis; however the recent version has regression-based equations for weight, area, and electric power that are more consistent with the "Naval Surface Warfare Center's Advanced Surface Ship Evaluation Tool (ASSET)" [6&7].

The design requirements must be defined in the model before starting the optimization process. These requirements and selected values for them are tabulated in Table 7.

VS	: Sustained Speed (knt)	**30**
Ve	: Endurance Speed (knt)	**20**
E	: Range (mile)	**4000**
TS	: Stores period (day)	**45**
WM	: Weight Margin (fraction of lightship weight)	**0.1**
KGMARG	: KG Margin (ft)	**0.5**
NO	: Manning, Number of Officers	**5**
NE	: Manning, Number of Enlisted	**53**

Table 7 The Design Requirements.

Several assumptions were made during the MATLAB modification of the mathematical model for optimization. First of all, the desired combat systems from the master payload and adjustments table were selected before the optimization process. This

ensured the Total Payload Weight (WP) to be constant, and therefore iteration for depths of stations became unnecessary. The selected systems are shown in the payload table (Table 8) below. To reduce the number of parameters, no auxiliary propulsion (APU) was assumed, so the weight (W237) and vertical center of gravity (VCG237) of auxiliary propulsion were set to zero. The Appendage Drag Coefficient (CDAPP) was assumed to be 2.8×10^{-5}. Moreover, a very simplified cost model (lead-ship end cost only) was added, using the former version of the MIT Functional Ship Design Synthesis Model. This ensured a reasonable estimate of the cost with respect to the different designs. See Appendix F for the MATLAB code of the model.

SYSTEM DESCRIPTION	WT KEY
NAVIGATION EQUIPMENT	
NAVIGATION SYSTEM	W420
SENSORS	
IFF	W455
MULTIPLE MODE/FUNCTION RADAR	W456
TOWED TORPEDO ALERTMENT ARRAY	W462
BOW SONAR	W463
ELECTRONIC WARFARE SENSORS	W466
ELECTRO OPTIC SENSOR	W466
WEAPONS SYSTEMS	
MISSILE WEAPON CONTROL SYSTEM	W482
INTEGRATED FIRE CONTROL SYSTEMS	W484
GUN	W711
AMMUNITION HANDLING	W712
AMMUNTION STOWAGE - READY SERVICE AND MAGAZINES	W713
LAUNCHING SYSTEMS, MISSILE (MK 48 Mod 2 - 8 Cells)	W721
TORPEDO TUBES ON DECK	W750
SURFACE TO SURFACE MISSILE LAUNCHER (Mk 140 LtWt - 2 Quad Launchers)	W721
MISSILES - 32 ESSM	WF21
AMMO - 300 Rounds	WF21
LIGHTWEIGHT ASW TORPEDOES - 6	WF21
SURFACE TO SURFACE MISSILES - 8	WF21
NETWORK SYSTEMS	
CIC ELEX	W411
EXCOMM + MINI CEC	W440
EMBARKED AIRCRAFT - AUTONOMOUS/REMOTE OPERATED VECHICLES	
Minehunting AUV/Remote Minehunting System	W478
UAV, Operating System	W495
LAMPS Mk III Fuel System	W542
LAMPS Mk III RAST System/Helo Control	W588
LAMPS Mk III Aviation Shop, Office	W665
LAMPS Mk III Torpedos (Mk 46 x 18), Sonobuoys and Pyrotechnics	WF22
LAMPS Mk III SH60 Helicopter and Hangar	WF23
LAMPS Mk III Aviation Support and Spares	WF26
LAMPS Mk III Fuel	WF42
COUNTERMEASURES	
PASSIVE ECM	W472

TORPEDO DECOY	W473
TORPEDO COUNTERMEASURES	W474
COUNTERMEASURES/DECOY STOWAGE	W763
COUNTERMEASURES/DECOY CANNISTERS - 100 RDS	WF21
PAYLOAD SUPPORT/AUX SYSTEMS	
RADAR - COOLING SYSTEM	W532
VLS AUXILIARY EQUIPMENT	W555
PAYLOAD OUTFIT ITEMS	
VLS ARMOR - LEVEL III HY-80	W164
GUN HY-80 ARMOR LEVEL II	W164
MISC SYSTEMS	
20mm STOWAGE	W763
20mm AMMUNITION - 8000 rounds	WF21

Table 8 Payload (MIT Model).

The MIT Functional Ship Design Synthesis Model was not formulated for the Parameter Space Investigation (PSI) technique. Therefore, the modification of the model covers the designation of the "design variables", the "functional relations" and "functional constraints", and the "performance criteria" and "criteria constraints" to portray the multi-criteria optimization problem.

There are forty-five design parameters to optimize. Sixteen of them are discrete variables. The first eight of these parameters are the basic design parameters. These forty-five parameters are as follows.

Basic design parameters:

LWL : (p1) Length (ft)

B : (p2) Beam (ft)

Ndecks : (p3) Number of Hull Decks. DISCRETE (2, 3, 4)

CP : (p4) Prismatic Coefficient. Typical range: 0.54 - 0.64

CX : (p5) Maximum Section Coefficient. Typical range: 0.70 - 0.85

HDKh : (p6) Avg. Hull Deck Height (ft)

BILGE : (p7) Bilge Height (ft)

HDKd : (p8) Avg. Deckhouse Deck Height (ft)

The propulsion system parameters:

NPENG : (p9) Number of Propulsion Engines. DISCRETE (1, 2, 3, 4)

eta : (p10) Mechanical Efficiency

NDIE : (p11) Deckhouse decks impacted by propulsion and generator

inlet/exhaust. DISCRETE (1, 2)

NHPIE : (p12) Hull decks impacted by propulsion inlet/exhaust. DISCRETE (1, 2, 3, 4)

WF46 : (p13) Lubrication Oil weight (lton)

NP : (p14) Number of propellers. DISCRETE (1, 2)

DP : (p15) Selected propeller diameter (ft)

LS : (p16) Selected shaft length (ft)

The ship control systems parameters:

ADB : (p17) Bridge area (ft^2)

WIC : (p18) Gyro/IC/Navigation Weight (W420, W430) (lton)

Nfins : (p19) Number of Fin Stabilizer Pairs. DISCRETE (0, 1)

The combat systems parameters:

CSD : (p20) Drag Coefficient.

ASD : (p21) Sonar Area (ft^2). DISCRETE (SQS-56: 27, SQS-53C: 215)

W498 : (p22) Sonar Dome Water Weight (lton)

VCG498 : (p23) Sonar Dome Water Vertical Center of Gravity (ft)

The deckhouse area requirements parameters:

ACOXO : (p24) Living Area for CO and XO (ft^2).

vf : (p25) Volume factor. DISCRETE (FFG 7: 3.5, DDG 51: 5.2)

CDHMAT : (p26) Deckhouse material. DISCRETE (Aluminum: 1, Steel: 2)

The auxiliary systems parameters:

CPS : (p27) Collective Protection System. DISCRETE (0, 1)
CPS = 0, if no CPS.

kWM : (p28) Miscellaneous (kW)

W593 : (p29) Environmental Support Systems Weight (lton)

W171 : (p30) Mast Weight (lton)

VWASTE : (p31) Waste Oil Volume (ft^3)

W598 : (p32) Aux Systems Operating Fluid Weight (lton)

The ship service generators parameters:

NG : (p33) Number of generators. DISCRETE (2, 3, 4)

NHeIE : (p34) Hull decks impacted by generator inlet/exhaust.

DISCRETE (1, 2, 3, 4)

The fuel parameter:

WBP : (p35) Burnable propulsion endurance fuel weight (lton)

The hull geometry parameters:

D10C : (p36) Constant for Depth at Station 10, D10xC.
Depth at Station 10(D10x) must be > or = D10MIN and
D10x = D10xC* D10MIN. Therefore select D10xC > or = 1

FP : (p37) Payload Weight Fraction.

WOFH : (p38) Hull Fittings (lton)

CHMAT : (p39) Hull Material. DISCRETE (0.93, 1.00)
(OS: CHMAT = 1.00; HTS: CHMAT = 0.93)

CBVC : (p40) Clean Ballast Volume Constant. DISCRETE (0, 1)
CBVC = 0 for compensated, 1 for uncompensated system

The resistance parameters:

LCB : (p41) The LCB from amidships as percent of length, (–) = aft

The propulsive power balance parameters:

PMF : (p42) Power Margin Factor (margin for concept design = 10%)

PC : (p43) Approximate Propulsive Coefficient.

Selection of propulsion engines:

SELECTP : (**p44**) DISCRETE (1, 2, 3, 4, 5, 6, 7)
(Data from the ASSET library in the Machinery Wizard)

Selection of Generators:

SELECTG : (**p45**) DISCRETE (1, 2, 3, 4, 5, 6, 7)
(Data from the ASSET library in the Machinery Wizard)

The following tables (Table 9 & Table 10) are for parameters number 44 and 45. The selection of propulsion engine and electrical generator comes before computations so that no assumption is needed for the percentage of "Generator Engine inlet/exhaust cross section" to the "Propulsion Engine inlet/exhaust cross section".

SELECTP	Type/Model	Weight (lton)	Length (ft)	Width (ft)	Height (ft)	Power (hp)	SFC (lbm/hp-hr)	Inlet X-sect (ft^2)	Exhaust X-sect (ft^2)
1	Diesel/PC 4.2V10	189.30	34.20	17.00	24.50	16270	0.3130	34.50	15.10
2	Diesel/F/PC2/16-DD	79.60	28.00	12.15	12.76	10400	0.3400	21.70	9.70
3	Diesel/PC 4.2V14	257.14	38.30	17.25	22.20	22778	0.3100	46.20	22.30
4	Diesel/PC 4.2V18	312.50	44.80	17.25	22.20	29286	0.3100	59.40	28.70
5	Gas Turbine/GE LM2500-30	3.10	15.65	5.20	5.20	26250	0.3930	99.60	51.00
6	Gas Turbine/Other (DDG 51)	3.10	15.65	5.20	5.20	25775	0.4100	106.00	53.10
7	Gas Turbine/GE LM5000	4.80	19.67	6.50	6.50	39100	0.3868	159.30	79.00

Table 9 The Propulsion Engines (MIT Model).

SELECTG	Model	Weight (lton)	Length (ft)	Width (ft)	Height (ft)	Power (hp)	SFC (lbm/hp-hr)	Inlet X-sect (ft^2)	Exhaust X-sect (ft^2)
1	CAT 3608 IL8	18.70	15.80	5.74	8.62	3390	0.3100	0.00	2.40
2	GM 16-645E5	16.80	17.64	5.64	9.25	3070	0.3800	0.00	2.20
3	Other (LSD 41)	11.40	15.18	6.46	9.79	2100	0.3700	0.00	2.10
4	F 38TD8-1/8-12	21.80	30.10	7.00	7.00	3500	0.3300	0.00	3.00
5	DDA 501-K34	0.60	7.50	2.80	2.60	4600	0.4730	24.00	11.70
6	DDA 570-KA	0.60	6.00	2.63	2.58	5965	0.4763	23.90	11.60
7	GE LM 500	0.57	7.20	2.80	2.80	4500	0.4812	20.90	10.20

Table 10 The Electrical Generators (MIT Model).

There are six criteria and eleven functional relations, which are subject to sixteen different functional constraints. Nine of the functional constraints are not rigid, i.e., their bounds have flexible values. Therefore, their functional relations can be treated as pseudo-criteria.

Functional relations:

f1 = kWG – kWGREQ

f2 = D10x – D10SL

f3 = GM (Ship Stability Characteristics)

f4 = PI – PIREQ

f5 = Eact – E

f6 = Ndecks – NHPIE

f7 = Ndecks – NHeIE

f8 = CLB

f9 = CBT

f10 = CDELTAL

f11 = CGMB (Ship Stability Characteristics)

kWG	: Generator power (each generator) (kW)
kWGREQ	: Installed Electrical Power required per generator (kW)
D10x	: Depth at Station 10
D10SL	: Depth at Station 10 due to the sheer line criteria
GM	: Metacentric Height
PI	: Total Shaft Horsepower
PIREQ	: Installed Shaft Horsepower required to achieve sustained speed.
E	: Range (mile) (Design requirement)
Eact	: Range (mile) (Actual)
Ndecks	: Number Hull Decks
NHPIE	: Number of Hull decks impacted by propulsion inlet/exhaust
NHeIE	: Number of Hull decks impacted by generator inlet/exhaust
CLB	: Length to Beam Ratio
CBT	: Beam to Draft Ratio:
CDELTAL	: Displacement to Length Ratio (lton/ft^3)
CGMB	: Transverse dynamic stability (GM/B)

Functional constraints:

f1	= kWG – kWGREQ	≥ 0
f2	= D10x – D10SL	≥ 0
f3	= GM	> 0
f4	= PI – PIREQ	≥ 0
f5	= Eact – E	≥ 0
f6	= Ndecks – NHPIE	≥ 0
f7	= Ndecks – NHeIE	≥ 0

Pseudo-criteria:

f5	= Eact – E		Pseudo-criterion (MIN)
f8	= CLB	≤ 10	Pseudo-criterion (MIN)
f8	= CLB	≥ 7.5	Pseudo-criterion (MAX)
f9	= CBT	≤ 3.7	Pseudo-criterion (MIN)
f9	= CBT	≥ 2.8	Pseudo-criterion (MAX)
f10	= CDELTAL	≤ 65	Pseudo-criterion (MIN)

f10	= CDELTAL	≥ 45	Pseudo-criterion (MAX)
f11	= CGMB	≤ 0.122	Pseudo-criterion (MIN)
f11	= CGMB	≥ 0.09	Pseudo-criterion (MAX)

Criteria:

c1	= ERRKW (%)	Criterion (MIN)
c2	= ERRPOWER (%)	Criterion (MIN)
c3	= ERRVOL (%)	Criterion (MAX)
c4	= ERRAREA (%)	Criterion (MAX)
c5	= ERRWEIGHT (%)	Criterion (MAX)
c6	= COST	Criterion (MIN)

ERRKW = 100 × (kWG – kWGREQ)/kWGREQ

(Percentage of the propulsion power error)

ERRPOWER = 100 × (PI – PIREQ)/PIREQ

(Percentage of the electrical power error)

ERRVOL = 100 × (VTA – VTR)/VTR

(Percentage of the volume error)

ERRAREA = 100 × (ATA – ATR)/ATR

(Percentage of the area error)

ERRWEIGHT= 100 × (DELTAFL – WT)/WT

(Percentage of the weight error)

kWG	: Generator power (each generator) (kW)
kWGREQ	: Installed Electrical Power required per generator (kW)
PI	: Total Shaft Horsepower
PIREQ	: Installed Shaft Horsepower required to achieve sustained speed.
VTR	: Total Required Volume (ft^3)
VTA	: Total Actual Volume (ft^3)
ATR	: Total Required Area (ft^2)
ATa	: Total Actual Area (ft^2)
WT	: Total Weight (lton)
DELTAFL	: Full Load Displacement (equal to full load weight) (lton)

Essentially ERRKW, ERRPOWER, ERRVOL, ERRAREA, ERRWEIGHT must be greater than or equal to zero. The functional constraints "$f1 \geq 0$" and "$f4 \geq 0$" ensure ERRKW and ERRPOWER to be greater than or equal to zero respectively, but these values might be very large. Hence, they were first minimized and then some reasonable maximum values were selected as criterion constraints. However, a small percentage of negative value is acceptable for ERRVOL, ERRAREA, and ERRWEIGHT. Therefore, those values were first maximized, and then reasonable minimum values were selected as criterion constraints. The sixth criteria, COST, was always minimized.

B. MULTI-CRITERIA ANALYSIS PROCESS

First, a Visual C++ code is written and compiled for the MATLAB model to establish the interface with MOVI software, referring to the bulk carrier design optimization model. After several tries using the original MATHCAD model and MATLAB version concurrently, the prototype shown in Table 11 was selected to start the optimization process, although the value of pseudo-criterion "$f9 = CBT \geq 2.8$" was "2.5519203". The main purpose of this multi-criteria analysis process is to improve this prototype.

As mentioned in Chapter II, the general strategy to determine the initial parallelepiped is to put the prototype in the center of it, unless the design variable constraints are already given. The boundaries of continuous parameters for the first optimization were determined using the prototype, with the exception of the third and fourth design variables, which have their own given boundaries. Since changing the design variable constraints leads to a new parallelepiped, after each optimization step, the design variable histograms (Appendix M) and the design variable tables were used to pick new values for the design variable constraints to further improve the results. The stiffness of criteria (and pseudo-criteria) constraints was increased after each optimization step as well. The chosen boundaries of variables and criteria constraints for each optimization are shown in Table 12 and Table 13 respectively, and each optimization step will be explained in this section.

Values of vectors:	
1 - LWL (p1)	356.2500
2 - B (p2)	39.3750
3 - Ndecks (p3) DISCRETE	2
4 - CP (p4)	0.6213
5 - CX (p5)	0.8031
6 - HDKh (p6)	8.5000
7 - BILGE (p7)	5.0000
8 - HDKd (p8)	8.0500
9 - NPENG (p9) DISCRETE	2
10 - eta (p10)	0.9700
11 - NDIE (p11) DISCRETE	2
12 - NHPIE (p12) DISCRETE	1
13 - WF46 (p13)	17.6000
14 - NP (p14) DISCRETE	1
15 - DP (p15)	12.0000
16 - LS (p16)	100.5000
17 - ADB (p17)	538.9000
18 - WIC: (p18)	43.8000
19 - Nfins (p19) DISCRETE	0
20 - CSD (p20)	0.2800
21 - ASD (p21) DISCRETE	27
22 - W498 (p22)	14.2000
23 - VCG498 (p23)	-3.0000
24 - ACOXO (p24)	325.0000
25 - vf (p25) DISCRETE	3.5
26 - CDHMAT (p26) DISCRETE	2
27 - CPS (p27) DISCRETE	1
28 - kWM (p28)	46.1000
29 - W593 (p29)	14.7000
30 - W171 (p30)	2.0000
31 - VWASTE (p31)	1700.0000
32 - W598 (p32)	60.5000
33 - NG (p33) DISCRETE	2
34 - NHeIE (p34) DISCRETE	2
35 - WBP (p35)	370.0000
36 - D10C (p36)	1.0000
37 - FP (p37)	0.0790
38 - WOFH (p38)	379.2000
39 - CHMAT (p39) DISCRETE	1
40 - CBVC (p40) DISCRETE	1
41 - LCB (p41)	-10.0000
42 - PMF (p42)	1.1000
43 - PC (p43)	0.6700
44 - SELECTP (p44) DISCRETE	5
45 - SELECTG (p45) DISCRETE	4

Values of functional relations:	
1 - f1 = kWG - kWGREQ >= 0	63.310373
2 - f2 = D10x - D10SL >= 0	0.0516928
3 - f3 = GM > 0	4.176925
4 - f4 = PI - PIREQ >= 0	4631.7511
5 - f5 = Eact - E >= 0	577.09656
6 - f6 = Ndecks - NHPIE >= 0	1
7 - f7 = Ndecks - NHeIE >= 0	0

Values of criteria:	
1 - ERRKW (%)	2.4860957
2 - ERRPOWER (%)	10.005241
3 - ERRVOL (%)	11.771601
4 - ERRAREA (%)	14.339138
5 - ERRWEIGHT (%)	1.0124392
6 - COST	555.72545
7 - f8 = CLB <= 10	9.047619
8 - f8 = CLB >= 7.5	9.047619
9 - f9 = CBT <= 3.7	2.5519203
10 - f9 = CBT >=2.8	2.5519203
11 - f10 = CDELTAL <= 65	68.241064
12 - f10 = CDELTAL >= 45	68.241064
13 - f11 = CGMB <= 0.122	0.1060806
14 - f11 = CGMB >= 0.09	0.1060806
15 - f5 = Eact - E	577.09656

Table 11 The Prototype.

Parameters	1st Optimization	2nd Optimization	3rd Optimization	4th Optimization	5th Optimization	6th Optimization
1 - LWL (p1)	300 — 400	300 — 370	328 — 370	360 - 372	360 - 372	360 - 372
2 - B (p2)	35 — 45	35 — 45	37 — 45	39 — 42	39 — 42	39 — 42
3 - Ndecks (p3) DISCRETE	2, 3, 4	2, 3	2, 3	2	2	2
4 - CP (p4)	0.54 — 0.64	0.54 — 0.64	0.54 — 0.64	0.57 — 0.64	0.57 — 0.64	0.57 — 0.64
5 - CX (p5)	0.70 — 0.85	0.70 — 0.85	0.70 — 0.85	0.80 — 0.85	0.80 — 0.85	0.80 — 0.85
6 - HDKh (p6)	8.3 — 8.7	8.3 — 8.7	8.34 — 8.70	8.38 — 8.70	8.38 — 8.70	8.38 — 8.70
7 - BILGE (p7)	4.5 — 5.5	4.4 — 5.4	4.4 — 5.4	4.3 — 5.3	4.3 — 5.3	4.3 — 5.3
8 - HDKd (p8)	7.85 — 8.25	7.85 — 8.25	7.89 — 8.21	7.90 — 8.21	7.90 — 8.21	7.90 — 8.21
9 - NPENG (p9) DISCRETE	1, 2, 3, 4	1, 2, 3	1, 2	2	2	2
10 - eta (p10)	0.95 — 0.99	0.95 — 0.99	0.954 — 0.986	0.96 — 0.99	0.96 — 0.99	0.96 — 0.99
11 - NDIE (p11) DISCRETE	1, 2	1, 2	1, 2	1	1	1
12 - NHPIE (p12) DISCRETE	1, 2, 3, 4	1, 2, 3	1, 2, 3	1, 2	1, 2	1, 2
13 - WF46 (p13)	15 — 20	13 —19	13 —19	15 —19	15 —19	15 —19
14 - NP (p14) DISCRETE	1, 2	1, 2	1, 2	1, 2	1, 2	1, 2
15 - DP (p15)	11 — 13	11 — 13	11 — 12.8	11 — 13	11 — 13	11 — 13
16 - LS (p16)	98 — 103	97 — 102	98 — 101.5	98 — 102	98 — 102	98 — 102
17 - ADB (p17)	500 — 580	493—573	493—557	510—561	510—561	510—561
18 - WIC: (p18)	43 — 44	34 — 44	34 — 43	36 — 43	36 — 43	36 — 43
19 - Nfins (p19) DISCRETE	0, 1	0, 1	0, 1	0, 1	0, 1	0, 1
20 - CSD (p20)	0.27 — 0.29	0.27 — 0.29	0.272 — 0.288	0.270 — 0.288	0.270 — 0.288	0.270 — 0.288
21 - ASD (p21) DISCRETE	27, 215	27, 215	27	27	27	27
22 - W498 (p22)	12 — 16	12 — 16	12.4 — 16	12.5 — 16.2	12.5 — 16.2	12.5 — 16.2
23 - VCG498 (p23)	-3.1 — -2.9	-3.08 — -2.96	-3.08 — -2.96	-3.07 — -2.98	-3.07 — -2.98	-3.07 — -2.98
24 - ACOXO (p24)	300 — 350	270 - 320	270 - 320	289 - 315	289 - 315	289 - 315
25 - vf (p25) DISCRETE	3.5, 5.2	3.5, 5.2	3.5, 5.2	3.5	3.5	3.5
26 - CDHMAT (p26) DISCRETE	1, 2	1, 2	1, 2	1, 2	1, 2	1, 2
27 - CPS (p27) DISCRETE	0, 1	0, 1	0, 1	0	0	0
28 - kWM (p28)	40 — 52	40 — 52	40 — 52	39 — 45	39 — 45	39 — 45
29 - W593 (p29)	12 — 17.5	12 — 17.5	12 — 17.5	14.6 — 16.5	14.6 — 16.5	14.6 — 16.5
30 - W171 (p30)	1.8 — 2.2	1.8 — 2.2	1.8 — 2.2	1.8 — 2.15	1.8 — 2.15	1.8 — 2.15
31 - VWASTE (p31)	1600 — 1800	1600 — 1800	1660 — 1780	1660 — 1780	1660 — 1780	1660 — 1780
32 - W598 (p32)	58 — 63	58 — 63	58 — 62.5	57 — 63	57 — 63	57 — 63
33 - NG (p33) DISCRETE	2, 3, 4	2, 3	2, 3	2	2	2
34 - NHelE (p34) DISCRETE	1, 2, 3, 4	1, 2, 3	1, 2, 3	2	2	2
35 - WBP (p35)	340 — 400	340 — 390	335 — 385	332 — 365	332 — 365	332 — 365
36 - D10C (p36)	1 — 1.2	1 — 1.2	1 — 1.2	1 — 1.1	1 — 1.1	1 — 1.1
37 - FP (p37)	0.04 — 0.21	0.01 — 0.21	0.07 — 0.11	0.074 — 0.083	0.074 — 0.083	0.074 — 0.083
38 - WOFH (p38)	360 — 400	360 — 400	356 — 384	350 — 382	350 — 382	350 — 382
39 - CHMAT (p39) DISCRETE	0.93, 1	0.93, 1	0.93, 1	0.93, 1	0.93, 1	0.93, 1
40 - CBVC (p40) DISCRETE	0, 1	0, 1	0, 1	0, 1	0, 1	0, 1
41 - LCB (p41)	-11 — -9	-11 — -9	-11 — -9	-10 — -9.3	-10 — -9.3	-10 — -9.3
42 - PMF (p42)	1.05 — 1.15	1.05 — 1.15	1.05 — 1.15	1.05 — 1.15	1.05 — 1.15	1.05 — 1.15
43 - PC (p43)	0.6 — 0.74	0.6 — 0.74	0.6 — 0.74	0.59 — 0.74	0.59 — 0.74	0.59 — 0.74
44 - SELECTP (p44) DISCRETE	1, 2, 3, 4, 5, 6, 7	1, 2, 3, 4, 5, 6, 7	1, 2, 3, 4, 5, 6, 7	5, 6	5, 6	5, 6
45 - SELECTG (p45) DISCRETE	1, 2, 3, 4, 5, 6, 7	1, 2, 3, 4, 5, 6, 7	1, 2, 3, 4, 5, 6, 7	1, 5	1, 5	1, 5

Table 12 The Boundaries of Parameters (Design Variable Constraints) for Each Optimization.

Criteria	1st Optimization	2nd Optimization	3rd Optimization	4th Optimization	5th Optimization	6th Optimization
1 - ERRKW (%)	< 70	< 70	< 50	< 10	< 10	< 5
2 - ERRPOWER (%)	< 51	< 51	< 50	< 10	< 10	< 5
3 - ERRVOL (%)	> -11	> -11	>= 0	>= 0	>= 0	>= 0
4 - ERRAREA (%)	> -11	> -11	>= 0	>= 0	>= 0	>= 0
5 - ERRWEIGHT (%)	—	> -20	>= 0	>= 0	>= 0	>= 0
6 - COST	—	—	—	—	—	< 553
7 - f8 = CLB <= 10	< 11	< 11	< 10.1	< 10	< 10	< 10
8 - f8 = CLB >= 7.5	>= 7.4	>= 7.4	> 7.4	> 7.5	> 7.5	> 7.5
9 - f9 = CBT <= 3.7	< 3.8	< 3.8	< 3.79	< 3.7	< 3.7	< 3.7
10 - f9 = CBT >=2.8	>= 2.7	>= 2.7	> 2.71	> 2.8	> 2.8	> 2.8
11 - f10 = CDELTAL <= 65	< 66	< 66	< 65.1	< 65	< 65	< 65
12 - f10 = CDELTAL >= 45	>= 44	>= 44	> 44.9	> 45	> 45	> 45
13 - f11 = CGMB <= 0.122	< 0.123	< 0.123	< 0.131	< 0.122	< 0.122	< 0.122
14 - f11 = CGMB >= 0.09	>= 0.08	>= 0.08	> 0.081	> 0.09	> 0.09	> 0.09
15 - f5 = Eact - E	< 1500	< 1500	< 500	< 400	< 400	< 200

Table 13 The Criterion Constraints for Each Optimization.

1. First Optimization Study

The main purpose of this step was to determine the initial design variable space (parallelepiped), apply flexible criteria constraints, and perform a "global search" for the feasible solutions. It is like taking the first shot in an artillery shooting range, and if the target does not get a hit, the range for the next shot will be changed in reference to the first range.

The boundaries of continuous parameters were determined using the prototype in Table 11, with the exception of the third and fourth design variables, which have their own given boundaries. The offered values for discrete design variables were included in this process to complete the initial parallelepiped (See Table 12).

The default generator, LP Tau, was used for this optimization run. Overall, 200,000 tests were conducted, 189,975 solutions did not satisfy the functional constraints, and 10,025 vectors entered the "Full Ordered Test Table". After analysis of the test table, although very flexible values of criteria (and pseudo-criteria) constraints were selected (See Table 13), only 7 vectors entered the truncated table. The feasible and Pareto optimal set had 7 vectors.

The criteria values of the prototype and the 7 feasible vectors are presented in Table 14. The minimum/maximum criteria values of those 7 feasible vectors are also in that table. The criteria values for the first two criteria, ERRKW (minimized) and ERRPOWER (minimized), were very large. ERRVOL, ERRAREA, and ERRWEIGHT were maximized, and a small percentage of negative values were tolerable for those three criteria. However, the maximum criterion value of ERRWEIGHT was "–16.8812", which was unacceptable. The last criterion, COST (minimized), had values greater then the same criterion value of the prototype. As a result, the prototype could not be improved.

The "criterion versus criterion" graphs for this step are shown in Appendix H. Particularly, Figure 61, Figure 65, Figure 68, Figure 70, and Figure 72 present the relationship between the fifth criterion, ERRWEIGHT (maximized), and the other criteria. It is apparent in those graphs that most of the infeasible solutions were gathered between approximately "–75" and "–35" for the fifth criterion.

Since the fifth criterion, ERRWEIGHT, had improper values, the effect of the design variables on this criterion was investigated. The graphs that show the dependency of "Criterion 5" on design variables for Pareto optimal solution number 32921 can be seen in Appendix N. Increasing the continuous design variables 1, 2, 6, 7, 8, 10, 13, 15, 16, 17, 18, 22, 24, 28, 29, 30, 31, 32, 35, 36, 37, and 38 causes a negative effect on the "Criterion 5". The discrete design variables 3, 9, 11, 14, 19, 25, 26, 27, 33, 39, 44, and 45 change "Criterion 5" as well. The other design variables have no effect. Among the continuous design variables, "Design Variable 37" has the most influence on the fifth criterion (See Figure 453 in Appendix N). Using the "Criterion versus Design Variable II" graphs, the dependency of Criterion 5 on "Design Variable 37" for the entire vector set was plotted to show this influence (See Figure 54).

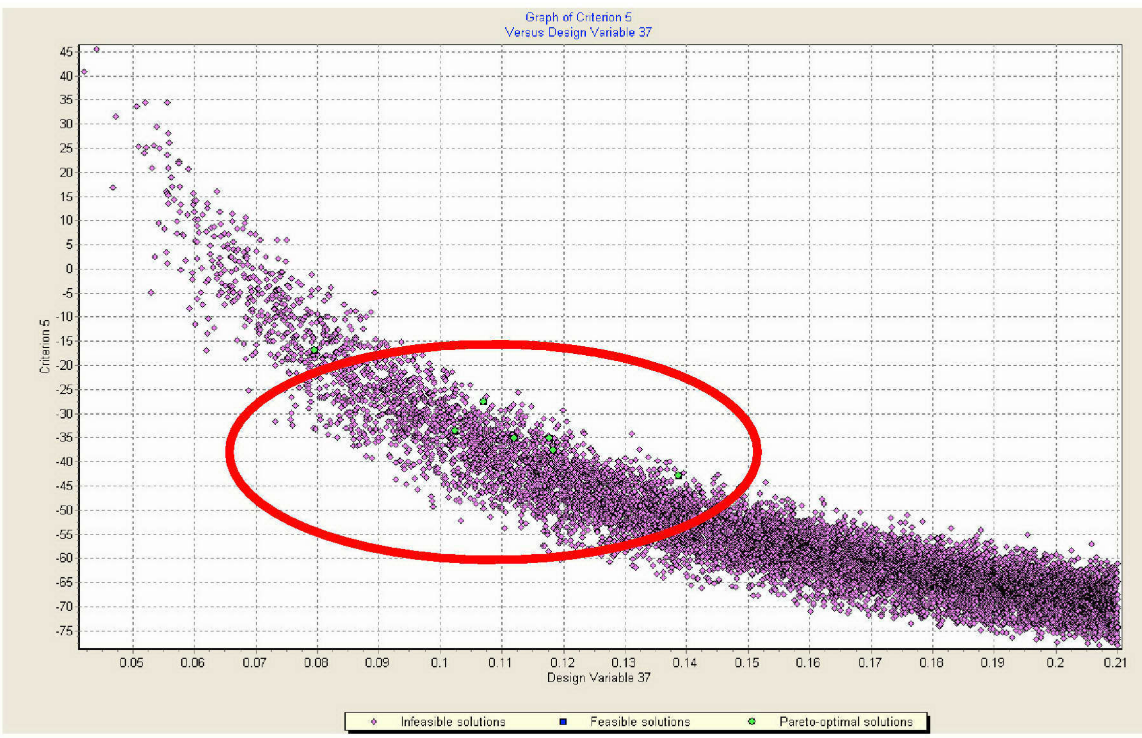

Figure 54 Criterion 5 versus Design Variable 37 – 1st Optimization.

The comparison of the minimum/maximum design variable values for the feasible set and the prototype, and the design variable constraints for this optimization run is presented in Table 15. Moreover, the feasible set histograms in Appendix M offer a more convenient visual inspection opportunity to investigate the design variable space. After

analyzing the design variable table, histograms, and the criterion versus design variable graphs, new values for the design variable constraints were selected to define the second parallelepiped (See Table 12).

Tests performed 200000
Feasible set contains: 7
Pareto-optimal set contains: 7
Number Generator: LP-Tau Net

Criteria		Prototype	32921	42129	100762	111350
Criterion #1	**ERRKW (%)**	2.4861	67.5170	65.0741	32.4957	0.7701
Criterion #2	**ERRPOWER (%)**	10.0052	9.5599	31.5208	26.7154	49.7089
Criterion #3	**ERRVOL (%)**	11.7716	27.7329	10.2123	0.9650	16.7188
Criterion #4	**ERRAREA (%)**	14.3391	32.2181	12.7648	1.2090	19.5245
Criterion #5	**ERRWEIGHT (%)**	1.0124	-16.8812	-35.0273	-27.5743	-37.5293
Criterion #6	**COST**	555.7255	593.0446	593.6998	568.6793	570.3146
Pseudo-Criteria		**Prototype**	**32921**	**42129**	**100762**	**111350**
Criterion #7	**f8 = CLB <= 10**	9.0476	8.0437	9.0826	8.8541	8.4999
Criterion #8	**f8 = CLB >= 7.5**	9.0476	8.0437	9.0826	8.8541	8.4999
Criterion #9	**f9 = CBT <= 3.7**	2.5519	2.8919	3.6964	2.8647	3.3380
Criterion #10	**f9 = CBT >=2.8**	**2.5519**	2.8919	3.6964	2.8647	3.3380
Criterion #11	**f10 = CDELTAL <= 65**	68.2411	65.8392	49.2311	60.5866	50.8278
Criterion #12	**f10 = CDELTAL >= 45**	68.2411	65.8392	49.2311	60.5866	50.8278
Criterion #13	**f11 = CGMB <= 0.122**	0.1061	0.1077	0.1007	0.1080	0.0890
Criterion #14	**f11 = CGMB >= 0.09**	0.1061	0.1077	0.1007	0.1080	0.0890
Criterion #15	**f5 = Eact - E**	577.0966	663.5402	1165.8918	1223.3569	1147.4750

Criteria		133985	143848	158349	Minimum	Maximum
Criterion #1	**ERRKW (%)**	31.6999	40.0005	8.6022	0.7701	67.5170
Criterion #2	**ERRPOWER (%)**	48.5032	39.1253	37.3035	9.5599	49.7089
Criterion #3	**ERRVOL (%)**	3.4904	-6.7187	24.4463	-6.7187	27.7329
Criterion #4	**ERRAREA (%)**	4.2446	-8.4763	29.7730	-8.4763	32.2181
Criterion #5	**ERRWEIGHT (%)**	-35.0323	-42.8251	-33.6327	-42.8251	-16.8812
Criterion #6	**COST**	548.3922	561.3962	588.8861	548.3922	593.6998
Pseudo-Criteria		**133985**	**143848**	**158349**	**Minimum**	**Maximum**
Criterion #7	**f8 = CLB <= 10**	8.6254	7.8701	8.7423	7.8701	9.0826
Criterion #8	**f8 = CLB >= 7.5**	8.6254	7.8701	8.7423	7.8701	9.0826
Criterion #9	**f9 = CBT <= 3.7**	3.1275	3.6272	3.5576	2.8647	3.6964
Criterion #10	**f9 = CBT >=2.8**	3.1275	3.6272	3.5576	2.8647	3.6964
Criterion #11	**f10 = CDELTAL <= 65**	47.1992	59.4805	47.2711	47.1992	65.8392
Criterion #12	**f10 = CDELTAL >= 45**	47.1992	59.4805	47.2711	47.1992	65.8392
Criterion #13	**f11 = CGMB <= 0.122**	0.0978	0.1135	0.0895	0.0890	0.1135
Criterion #14	**f11 = CGMB >= 0.09**	0.0978	0.1135	0.0895	0.0890	0.1135
Criterion #15	**f5 = Eact - E**	821.7482	995.2834	732.8596	663.5402	1223.3569

Table 14 Table of Criteria – 1st Optimization.

Tests performed 200000
Feasible set contains: 7
Pareto-optimal set contains: 7
Number Generator: LP-Tau Net

Parameters	Prototype	Minimum	Maximum	Design Variable Constraints
1 - LWL (p1)	356.2500	309.1984	369.2722	300 — 400
2 - B (p2)	39.3750	37.8344	44.7264	35 — 45
3 - Ndecks (p3) DISCRETE	2	2	3	2, 3, 4
4 - CP (p4)	0.6213	0.5417	0.6391	0.54 — 0.64
5 - CX (p5)	0.8031	0.7047	0.8379	0.70 — 0.85
6 - HDKh (p6)	8.5000	8.3134	8.6974	8.3 — 8.7
7 - BILGE (p7)	5.0000	4.5848	5.3278	4.5 — 5.5
8 - HDKd (p8)	8.0500	7.8531	8.2430	7.85 — 8.25
9 - NPENG (p9) DISCRETE	2	2	2	1, 2, 3, 4
10 - eta (p10)	0.9700	0.9526	0.9797	0.95 — 0.99
11 - NDIE (p11) DISCRETE	2	1	2	1, 2
12 - NHPIE (p12) DISCRETE	1	1	3	1, 2, 3, 4
13 - WF46 (p13)	17.6000	15.1999	18.5871	15 — 20
14 - NP (p14) DISCRETE	1	2	2	1, 2
15 - DP (p15)	12.0000	11.2718	12.9119	11 — 13
16 - LS (p16)	100.5000	98.3318	101.7016	98 — 103
17 - ADB (p17)	538.9000	503.1799	568.5843	500 — 580
18 - WIC: (p18)	43.8000	43.0406	43.7247	43 — 44
19 - Nfins (p19) DISCRETE	0	0	1	0, 1
20 - CSD (p20)	0.2800	0.2705	0.2892	0.27 — 0.29
21 - ASD (p21) DISCRETE	27	27	27	27, 215
22 - W498 (p22)	14.2000	13.5479	15.5089	12 — 16
23 - VCG498 (p23)	-3.0000	-3.0739	-2.9601	-3.1 — -2.9
24 - ACOXO (p24)	325.0000	300.5491	340.0627	300 — 350
25 - vf (p25) DISCRETE	3.5	3.5	5.2	3.5, 5.2
26 - CDHMAT (p26) DISCRETE	2	1	2	1, 2
27 - CPS (p27) DISCRETE	1	0	1	0, 1
28 - kWM (p28)	46.1000	42.8726	51.8258	40 — 52
29 - W593 (p29)	14.7000	13.0332	17.4130	12 — 17.5
30 - W171 (p30)	2.0000	1.8659	2.1733	1.8 — 2.2
31 - VWASTE (p31)	1700.0000	1613.3026	1790.5380	1600 — 1800
32 - W598 (p32)	60.5000	58.2516	62.1804	58 — 63
33 - NG (p33) DISCRETE	2	2	3	2, 3, 4
34 - NHelE (p34) DISCRETE	2	1	3	1, 2, 3, 4
35 - WBP (p35)	370.0000	350.4594	385.3232	340 — 400
36 - D10C (p36)	1.0000	1.0165	1.1908	1 — 1.2
37 - FP (p37)	0.0790	0.0795	0.1386	0.04 — 0.21
38 - WOFH (p38)	379.2000	361.9756	396.4572	360 — 400
39 - CHMAT (p39) DISCRETE	1	0.93	1	0.93, 1
40 - CBVC (p40) DISCRETE	1	0	1	0, 1
41 - LCB (p41)	-10.0000	-10.3811	-9.7345	-11 — -9
42 - PMF (p42)	1.1000	1.0505	1.1363	1.05 — 1.15
43 - PC (p43)	0.6700	0.6209	0.7338	0.6 — 0.74
44 - SELECTP (p44) DISCRETE	5	5	6	1, 2, 3, 4, 5, 6, 7
45 - SELECTG (p45) DISCRETE	4	3	7	1, 2, 3, 4, 5, 6, 7

Table 15 Design Variable Values and Constraints – 1st Optimization

2. Second Optimization Study

The prototype could not be improved in the first optimization; hence, a new parallelepiped was defined. In other words, in the artillery analogy, the target did not get a hit, so the range for the next shot was changed in reference to the first range. Again, the default generator, LP Tau, was used for this second "global search". Overall, 200,000 tests were conducted, 188,669 solutions did not satisfy the functional constraints, and 11,331 vectors entered the "Full Ordered Test Table". During the analysis of the test table, the stiffness of criteria (and pseudo-criteria) constraints was increased (See Table 13), and 9 vectors entered the truncated table. The feasible set had 9 vectors and the Pareto optimal set had 8 vectors.

Table 16 shows the comparison of the criteria values of the prototype and the 9 feasible vectors, including the minimum/maximum criteria values of the feasible set. The "criterion versus criterion" graphs for this step are in Appendix I. The results are better than the first optimization results. For example, the "Criterion 1" (ERRKW-minimized) versus "Criterion 2" (ERRPOWER-minimized) graphs (See Figure 58, Appendix H and Figure 73, Appendix I) for the first two optimization steps reveal this improvement, since the Pareto optimal solutions are closer to the origin (0, 0) for the second step.

On the other hand, the feasible set criteria values were not better than the prototype criteria values. Most significantly, the criterion values of ERRWEIGHT (maximized) were between "–19.6645" and "–3.3062", which was still unsatisfactory. The "criterion versus criterion graphs" (See Figure 76, Figure 80, Figure 83, Figure 85, and Figure 87 in Appendix I) show that most of the infeasible solutions were still gathered between approximately –75 and –35 for the fifth criterion. Overall, the results were superior to the first optimization results, but still the prototype could not be improved.

The dependency of Criterion 5 on "Design Variable 37" for the entire vector set is presented in Figure 55. The feasible set histogram of the "Design Variable 37" is also shown in Figure 365 (Appendix M). After analysis of these figures, the lower and upper bounds for this parameter were selected to be "0.07" and "0.11" respectively for the next "global search". The new values for the remaining design variable constraints were

determined using the design variable table (See Table 17) and the feasible set histograms (Appendix M). In fact, one of the discrete variables, "Design Variable 21", was decided to be a constant. Therefore, the number of design variables became forty-four. The third parallelepiped defined by the new constraints is available in Table 12.

Tests performed 200000
Feasible set contains: 9
Pareto-optimal set contains: 8
Number Generator: LP-Tau Net
NP : NOT PARETO

Criteria		Prototype	43363	50211 NP	56119	56485	112398
Criterion #1	ERRKW (%)	2.4861	6.5279	59.6998	25.8950	6.0586	20.0685
Criterion #2	ERRPOWER (%)	10.0052	36.3406	10.3461	7.7281	13.6972	27.5544
Criterion #3	ERRVOL (%)	11.7716	14.3607	8.1309	34.0227	13.7387	11.4045
Criterion #4	ERRAREA (%)	14.3391	16.7333	10.2626	37.8876	16.2896	12.9361
Criterion #5	ERRWEIGHT (%)	1.0124	-19.6645	-12.5483	-3.3062	-17.7817	-19.4181
Criterion #6	COST	555.7255	542.6230	589.3882	548.2111	557.5144	546.4221
Pseudo-Criteria		**Prototype**	**43363**	**50211 NP**	**56119**	**56485**	**112398**
Criterion #7	f8 = CLB <= 10	9.0476	9.0949793	8.89326	8.5089931	8.3795052	8.7202654
Criterion #8	f8 = CLB >= 7.5	9.0476	9.0949793	8.89326	8.5089931	8.3795052	8.7202654
Criterion #9	f9 = CBT <= 3.7	2.5519	3.0225494	2.9554121	2.8751175	2.8752871	3.0940197
Criterion #10	f9 = CBT >=2.8	**2.5519**	3.0225494	2.9554121	2.8751175	2.8752871	3.0940197
Criterion #11	f10 = CDELTAL <= 65	68.2411	53.528477	65.390617	64.375694	63.093407	63.727421
Criterion #12	f10 = CDELTAL >= 45	68.2411	53.528477	65.390617	64.375694	63.093407	63.727421
Criterion #13	f11 = CGMB <= 0.122	0.1061	0.1109135	0.1065029	0.0839916	0.0841565	0.1099043
Criterion #14	f11 = CGMB >= 0.09	0.1061	0.1109135	0.1065029	0.0839916	0.0841565	0.1099043
Criterion #15	f5 = Eact - E	577.0966	799.5451	755.92902	94.972931	493.14697	883.43219

Criteria		122557	150027	157225	175795	Minimum	Maximum
Criterion #1	ERRKW (%)	30.0881	43.5823	25.6585	29.8063	6.0586	59.6998
Criterion #2	ERRPOWER (%)	6.7358	1.6650	17.6088	42.8981	1.6650	42.8981
Criterion #3	ERRVOL (%)	16.0311	10.2930	5.1115	13.4895	5.1115	34.0227
Criterion #4	ERRAREA (%)	19.3321	12.4320	6.1515	15.5529	6.1515	37.8876
Criterion #5	ERRWEIGHT (%)	-15.7344	-17.1314	-11.8236	-16.0627	-19.6645	-3.3062
Criterion #6	COST	564.5132	581.4986	544.9581	544.2915	542.6230	589.3882
Pseudo-Criteria		**122557**	**150027**	**157225**	**175795**	**Minimum**	**Maximum**
Criterion #7	f8 = CLB <= 10	8.4781637	8.0826225	8.5644112	8.6952715	8.0826	9.0950
Criterion #8	f8 = CLB >= 7.5	8.4781637	8.0826225	8.5644112	8.6952715	8.0826	9.0950
Criterion #9	f9 = CBT <= 3.7	2.9905767	3.0226102	2.7744844	2.8658156	2.7745	3.0940
Criterion #10	f9 = CBT >=2.8	2.9905767	3.0226102	2.7744844	2.8658156	2.7745	3.0940
Criterion #11	f10 = CDELTAL <= 65	62.858963	61.430916	65.226555	57.69326	53.5285	65.3906
Criterion #12	f10 = CDELTAL >= 45	62.858963	61.430916	65.226555	57.69326	53.5285	65.3906
Criterion #13	f11 = CGMB <= 0.122	0.0913275	0.1192857	0.0879447	0.0844758	0.0840	0.1193
Criterion #14	f11 = CGMB >= 0.09	0.0913275	0.1192857	0.0879447	0.0844758	0.0840	0.1193
Criterion #15	f5 = Eact - E	417.41263	1261.9762	512.4834	1080.527	94.9729	1261.9762

Table 16 Table of Criteria – 2nd Optimization.

Tests performed 200000
Feasible set contains: 9
Pareto-optimal set contains: 8
Number Generator: LP-Tau Net

	Pareto-optimal set			
Parameters	**Prototype**	**Minimum**	**Maximum**	**Design Variable Constraints**
1 - LWL (p1)	356.2500	330.8787	364.7652	300 — 370
2 - B (p2)	39.3750	37.9436	44.1642	35 — 45
3 - Ndecks (p3) DISCRETE	2	2	3	2, 3
4 - CP (p4)	0.6213	0.5414	0.6371	0.54 — 0.64
5 - CX (p5)	0.8031	0.7243	0.8237	0.70 — 0.85
6 - HDKh (p6)	8.5000	8.3644	8.6983	8.3 — 8.7
7 - BILGE (p7)	5.0000	4.4007	5.3397	4.4 — 5.4
8 - HDKd (p8)	8.0500	7.9281	8.2093	7.85 — 8.25
9 - NPENG (p9) DISCRETE	2	1	2	1, 2, 3
10 - eta (p10)	0.9700	0.9540	0.9853	0.95 — 0.99
11 - NDIE (p11) DISCRETE	2	1	2	1, 2
12 - NHPIE (p12) DISCRETE	1	1	3	1, 2, 3
13 - WF46 (p13)	17.6000	13.0336	18.9503	13 —19
14 - NP (p14) DISCRETE	1	1	2	1, 2
15 - DP (p15)	12.0000	11.1624	12.7438	11 — 13
16 - LS (p16)	100.5000	98.4167	101.2076	97 — 102
17 - ADB (p17)	538.9000	498.4877	553.7587	493—573
18 - WIC: (p18)	43.8000	34.5000	42.8299	34 — 44
19 - Nfins (p19) DISCRETE	0	0	1	0, 1
20 - CSD (p20)	0.2800	0.2731	0.2865	0.27 — 0.29
21 - ASD (p21) DISCRETE	27	27	27	27, 215
22 - W498 (p22)	14.2000	12.5175	15.9633	12 — 16
23 - VCG498 (p23)	-3.0000	-3.0733	-2.9603	-3.08 — -2.96
24 - ACOXO (p24)	325.0000	272.7168	317.6143	270 - 320
25 - vf (p25) DISCRETE	3.5	3.5	5.2	3.5, 5.2
26 - CDHMAT (p26) DISCRETE	2	1	2	1, 2
27 - CPS (p27) DISCRETE	1	0	1	0, 1
28 - kWM (p28)	46.1000	40.7856	51.7565	40 — 52
29 - W593 (p29)	14.7000	12.0427	17.4680	12 — 17.5
30 - W171 (p30)	2.0000	1.8159	2.1500	1.8 — 2.2
31 - VWASTE (p31)	1700.0000	1662.8090	1776.8219	1600 — 1800
32 - W598 (p32)	60.5000	59.0569	62.3992	58 — 63
33 - NG (p33) DISCRETE	2	2	3	2, 3
34 - NHeIE (p34) DISCRETE	2	1	2	1, 2, 3
35 - WBP (p35)	370.0000	340.2983	381.6737	340 — 390
36 - D10C (p36)	1.0000	1.0212	1.1910	1 — 1.2
37 - FP (p37)	0.0790	0.0780	0.1056	0.01 — 0.21
38 - WOFH (p38)	379.2000	360.1154	382.3235	360 — 400
39 - CHMAT (p39) DISCRETE	1	0.93	1	0.93, 1
40 - CBVC (p40) DISCRETE	1	0	1	0, 1
41 - LCB (p41)	-10.0000	-10.8797	-9.0742	-11 — -9
42 - PMF (p42)	1.1000	1.0581	1.1409	1.05 — 1.15
43 - PC (p43)	0.6700	0.6065	0.7343	0.6 — 0.74
44 - SELECTP (p44) DISCRETE	5	5	7	1, 2, 3, 4, 5, 6, 7
45 - SELECTG (p45) DISCRETE	4	1	7	1, 2, 3, 4, 5, 6, 7

Table 17 Design Variable Values and Constraints – 2^{nd} Optimization.

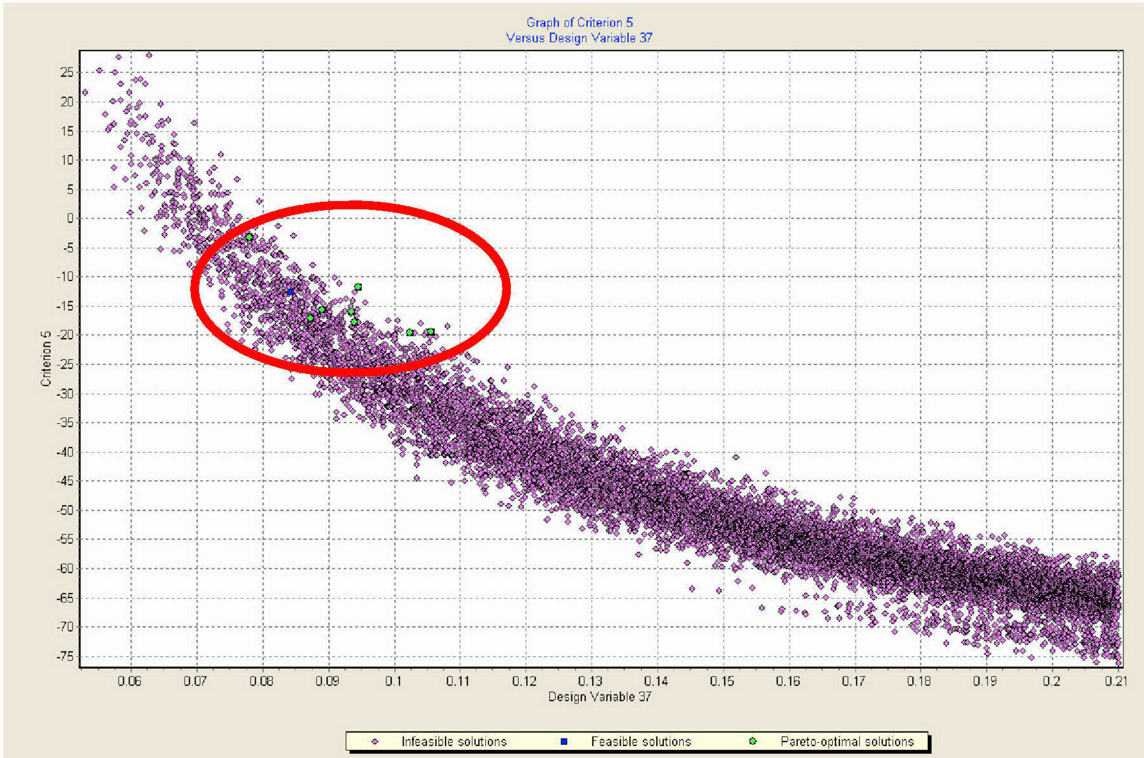

Figure 55 Criterion 5 versus Design Variable 37 – 2nd Optimization.

3. Third Optimization Study

Since the result of the second step was not satisfactory, another "global search" was conducted in the third design variable space. Again, the default generator, LP Tau, was used. Overall, 200,000 tests were conducted, 181,447 solutions did not satisfy the functional constraints, and 18,553 vectors entered the "Full Ordered Test Table". The stiffness of criteria (and pseudo-criteria) constraints was significantly increased so that no negative values were allowed for ERRVOL, ERRAREA, and ERRWEIGHT (See Table 13). As a result, 3 vectors entered the truncated table. The feasible and the Pareto optimal set had 3 vectors.

The criteria values of the prototype and the 3 feasible vectors in Table 18 prove that the prototype was improved. The "criterion versus criterion" graphs for this step are presented in Appendix J. These graphs were analyzed, and the best solution vector for each criterion versus criterion comparison was selected (See Table 19). In general, the vector "#108455" was the most preferable solution among the three Pareto optimal vectors.

Tests performed 200000
Feasible set contains: 3
Pareto-optimal set contains: 3
Number Generator: LP-Tau Net

Criteria		Prototype	17311	108455	171279	Minimum	Maximum
Criterion #1	**ERRKW (%)**	2.4861	40.0043	6.9164	6.2190	6.2190	40.0043
Criterion #2	**ERRPOWER (%)**	10.0052	10.6648	9.9123	12.7196	9.9123	12.7196
Criterion #3	**ERRVOL (%)**	11.7716	23.3074	27.6015	10.9841	10.9841	27.6015
Criterion #4	**ERRAREA (%)**	14.3391	27.1718	31.2549	13.6040	13.6040	31.2549
Criterion #5	**ERRWEIGHT (%)**	1.0124	2.1167	1.9407	3.1097	1.9407	3.1097
Criterion #6	**COST**	555.7255	558.6413	548.2029	545.2049	545.2049	558.6413
Pseudo-Criteria		**Prototype**	**17311**	**108455**	**171279**	**Minimum**	**Maximum**
Criterion #7	**f8 = CLB <= 10**	9.0476	8.9050	8.9143	9.0206	8.9050	9.0206
Criterion #8	**f8 = CLB >= 7.5**	9.0476	8.9050	8.9143	9.0206	8.9050	9.0206
Criterion #9	**f9 = CBT <= 3.7**	2.5519	2.9164	2.9267	2.7215	2.7215	2.9267
Criterion #10	**f9 = CBT >=2.8**	**2.5519**	2.9164	2.9267	2.7215	2.7215	2.9267
Criterion #11	**f10 = CDELTAL <= 65**	68.2411	64.2897	63.3161	62.9397	62.9397	64.2897
Criterion #12	**f10 = CDELTAL >= 45**	68.2411	64.2897	63.3161	62.9397	62.9397	64.2897
Criterion #13	**f11 = CGMB <= 0.122**	0.1061	0.1161	0.0815	0.0852	0.0815	0.1161
Criterion #14	**f11 = CGMB >= 0.09**	0.1061	0.1161	0.0815	0.0852	0.0815	0.1161
Criterion #15	**f5 = Eact - E**	577.0966	379.4735	295.9995	67.2061	67.2061	379.4735

Table 18 Table of Criteria – 3rd Optimization.

Figure 88	Criterion 1 (Minimized) vs. Criterion 2 (Minimized)	**#108455**
Figure 89	Criterion 1 (Minimized) vs. Criterion 3 (Maximized)	**#108455**
Figure 90	Criterion 1 (Minimized) vs. Criterion 4 (Maximized)	**#108455**
Figure 91	Criterion 1 (Minimized) vs. Criterion 5 (Maximized)	**#171279**
Figure 92	Criterion 1 (Minimized) vs. Criterion 6 (Minimized)	**#171279**
Figure 93	Criterion 2 (Minimized) vs. Criterion 3 (Maximized)	**#108455**
Figure 94	Criterion 2 (Minimized) vs. Criterion 4 (Maximized)	**#108455**
Figure 95	Criterion 2 (Minimized) vs. Criterion 5 (Maximized)	**#17311**
Figure 96	Criterion 2 (Minimized) vs. Criterion 6 (Minimized)	**#108455**
Figure 97	Criterion 3 (Maximized) vs. Criterion 4 (Maximized)	**#108455**
Figure 98	Criterion 3 (Maximized) vs. Criterion 5 (Maximized)	**#17311**
Figure 99	Criterion 3 (Maximized) vs. Criterion 6 (Minimized)	**#108455**
Figure 100	Criterion 4 (Maximized) vs. Criterion 5 (Maximized)	**#17311**
Figure 101	Criterion 4 (Maximized) vs. Criterion 6 (Minimized)	**#108455**
Figure 102	Criterion 5 (Maximized) vs. Criterion 6 (Minimized)	**#171279**

Table 19 The Best Solution Vector for Each Criterion versus Criterion Comparison – 3rd Optimization.

The complexity of improving on the prototype is obvious, since only three Pareto optimal solutions were obtained as a result of 200,000 tests. The design variable values for these three solutions are tabulated in Table 20.

The dependency of Criterion 5 on “Design Variable 37” for the entire vector set became more linear, since a smaller range was selected for this variable (See Figure 56). The lower and upper bounds for the next optimization range were selected to be “0.074” and “0.083” respectively, which is, in fact, a much smaller range. One of the discrete variables, “Design Variable 21”, was previously decided to be a constant. After analysis of the design variable table and the histograms (Appendix M), the discrete design variables 3, 9, 11, 25, 27, 33, and 34 turned out to be constants. As a result, the number of design variables is reduced to thirty-seven. The fourth design variable space defined by the new constraints is available in Table 12.

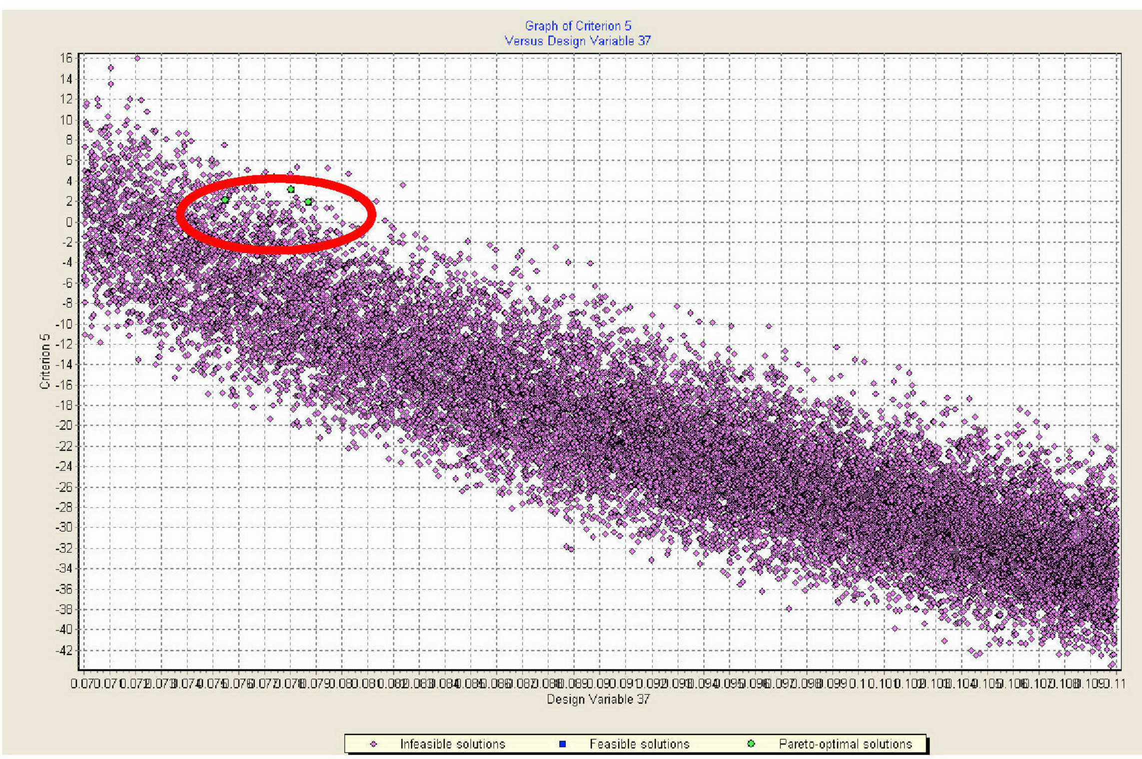

Figure 56 Criterion 5 versus Design Variable 37 – 3rd Optimization.

Tests performed 200000
Feasible set contains: 3
Pareto-optimal set contains: 3
Number Generator: LP-Tau Net

Parameters	Prototype	171279	108455	17311	Minimum	Maximum
1 - LWL (p1)	356.2500	367.4937	365.7174	368.9759	365.7174	368.9759
2 - B (p2)	39.3750	40.7392	41.0258	41.4348	40.7392	41.4348
3 - Ndecks (p3) DISCRETE	2	2	2	2	2	2
4 - CP (p4)	0.6213	0.5801	0.6086	0.6399	0.5801	0.6399
5 - CX (p5)	0.8031	0.8410	0.8468	0.8132	0.8132	0.8468
6 - HDKh (p6)	8.5000	8.5585	8.4203	8.5255	8.4203	8.5585
7 - BILGE (p7)	5.0000	4.4113	5.2265	4.5641	4.4113	5.2265
8 - HDKd (p8)	8.0500	8.1872	8.0782	8.0592	8.0592	8.1872
9 - NPENG (p9) DISCRETE	2	2	2	2	2	2
10 - eta (p10)	0.9700	0.9657	0.9843	0.9751	0.9657	0.9843
11 - NDIE (p11) DISCRETE	2	1	1	1	1	1
12 - NHPIE (p12) DISCRETE	1	2	1	2	1	2
13 - WF46 (p13)	17.6000	18.8006	15.6267	16.3466	15.6267	18.8006
14 - NP (p14) DISCRETE	1	2	1	2	1	2
15 - DP (p15)	12.0000	11.4021	11.1706	12.7151	11.1706	12.7151
16 - LS (p16)	100.5000	98.9887	101.1986	98.3096	98.3096	101.1986
17 - ADB (p17)	538.9000	519.8215	522.8511	556.2871	519.8215	556.2871
18 - WIC: (p18)	43.8000	37.7918	38.2641	41.5369	37.7918	41.5369
19 - Nfins (p19) DISCRETE	0	0	0	1	0	1
20 - CSD (p20)	0.2800	0.2824	0.2774	0.2845	0.2774	0.2845
21 - ASD (p21) DISCRETE	27	27	27	27	27	27
22 - W498 (p22)	14.2000	14.6463	15.8549	12.8818	12.8818	15.8549
23 - VCG498 (p23)	-3.0000	-3.0537	-3.0332	-3.0332	-3.0537	-3.0332
24 - ACOXO (p24)	325.0000	293.0795	312.8463	301.7886	293.0795	312.8463
25 - vf (p25) DISCRETE	3.5	3.5	3.5	3.5	3.5	3.5
26 - CDHMAT (p26) DISCRETE	2	1	2	1	1	2
27 - CPS (p27) DISCRETE	1	0	0	0	0	0
28 - kWM (p28)	46.1000	41.0762	43.1649	40.2289	40.2289	43.1649
29 - W593 (p29)	14.7000	16.2652	15.2778	15.8116	15.2778	16.2652
30 - W171 (p30)	2.0000	1.8400	1.9358	2.0830	1.8400	2.0830
31 - VWASTE (p31)	1700.0000	1700.7103	1766.9839	1693.7390	1693.7390	1766.9839
32 - W598 (p32)	60.5000	58.0620	62.1378	58.2836	58.0620	62.1378
33 - NG (p33) DISCRETE	2	2	2	2	2	2
34 - NHeIE (p34) DISCRETE	2	2	2	2	2	2
35 - WBP (p35)	370.0000	339.3905	360.1652	358.5550	339.3905	360.1652
36 - D10C (p36)	1.0000	1.0653	1.0540	1.0573	1.0540	1.0653
37 - FP (p37)	0.0790	0.0780	0.0787	0.0755	0.0755	0.0787
38 - WOFH (p38)	379.2000	359.6434	379.6504	362.5155	359.6434	379.6504
39 - CHMAT (p39) DISCRETE	1	1	0.93	1	0.93	1
40 - CBVC (p40) DISCRETE	1	1	0	0	0	1
41 - LCB (p41)	-10.0000	-9.4099	-9.8478	-9.8299	-9.8478	-9.4099
42 - PMF (p42)	1.1000	1.0635	1.1260	1.0934	1.0635	1.1260
43 - PC (p43)	0.6700	0.6081	0.6657	0.7253	0.6081	0.7253
44 - SELECTP (p44) DISCRETE	5	5	6	6	5	6
45 - SELECTG (p45) DISCRETE	4	1	1	5	1	5

Table 20 Design Variable Values – 3rd Optimization.

4. Fourth Optimization Study

After correction of the problem statement by reducing the number of design variables and redefining the design variable constraints, another search for the optimal solutions was conducted in the new design variable space. Again, the default generator, LP Tau, was used. Overall, 200,000 tests were conducted, 56,407 solutions did not satisfy the functional constraints, and 143,593 vectors entered the "Full Ordered Test Table". The stiffness of criteria (and pseudo-criteria) constraints was again increased so that all of the pseudo-criteria became rigid (See Table 13). As a result, 2,161 vectors entered the truncated table. The feasible set had 2,161 vectors and the Pareto optimal set had 208 vectors. Actually, the fact that there are 208 Pareto optimal vectors does not mean there are 208 completely different design solutions. Some of the designs might be similar.

The criteria values of the prototype and the minimum/maximum criteria values of the Pareto optimal set in Table 22 prove that the results were better than the third optimization results, and the prototype was improved. The "criterion versus criterion" graphs for this step are presented in Appendix K. Figure 103, Figure 105, Figure 107, Figure 109, and Figure 111 show that the solutions clustered into four different zones for "Criterion 1" (ERRKW-minimized). These zones were from values of approximately 2 to 5, 6 to 8, 38 to 42, and 43 to 46. The Pareto optimal solutions were mostly in the first zone from values of approximately 2 to 5. Moreover, Figure 111, Figure 119, Figure 125, Figure 129, and Figure 131 show that the solutions clustered into two different zones for "Criterion 6" (COST-minimized). These zones were from values of approximately 538 to 553, and 554 to 568. The Pareto optimal solutions were in the first zone from values of approximately 538 to 553. All figures in Appendix K show distinctive cutoff lines that reveal where the criteria constraints exist. The feasible solution points always fell either above or below, or to the left or right, of their respective maximum or minimum constraint value.

The maximum and minimum design variable values for the feasible and Pareto optimal set are in Table 21. Analysis of the feasible set histograms in Appendix M reveals that the distribution of variable values within their ranges was improved and variable values were more evenly distributed.

Tests performed 200000
Feasible set contains: 2161
Pareto-optimal set contains: 208
Number Generator: LP-Tau Net

		Feasible set		Pareto-optimal set	
Parameters	**Prototype**	**Minimum**	**Maximum**	**Minimum**	**Maximum**
1 - LWL (p1)	356.2500	360.0089	371.9978	360.0641	371.9858
2 - B (p2)	39.3750	39.0415	41.9986	39.3469	41.9941
3 - Ndecks (p3) DISCRETE	2	2	2	2	2
4 - CP (p4)	0.6213	0.5717	0.6400	0.5789	0.6400
5 - CX (p5)	0.8031	0.8000	0.8500	0.8000	0.8500
6 - HDKh (p6)	8.5000	8.3800	8.6999	8.3802	8.6987
7 - BILGE (p7)	5.0000	4.3002	5.2999	4.3008	5.2916
8 - HDKd (p8)	8.0500	7.9002	8.2097	7.9008	8.2097
9 - NPENG (p9) DISCRETE	2	2	2	2	2
10 - eta (p10)	0.9700	0.9600	0.9900	0.9600	0.9898
11 - NDIE (p11) DISCRETE	2	1	1	1	1
12 - NHPIE (p12) DISCRETE	1	1	2	1	2
13 - WF46 (p13)	17.6000	15.0002	18.9985	15.0002	18.9772
14 - NP (p14) DISCRETE	1	1	2	1	2
15 - DP (p15)	12.0000	11.0004	12.9991	11.0025	12.9966
16 - LS (p16)	100.5000	98.0008	101.9988	98.0008	101.9339
17 - ADB (p17)	538.9000	510.0078	560.9940	510.0078	560.7101
18 - WIC: (p18)	43.8000	36.0026	42.9962	36.0026	42.9048
19 - Nfins (p19) DISCRETE	0	0	1	1	1
20 - CSD (p20)	0.2800	0.2700	0.2880	0.2700	0.2879
21 - ASD (p21) DISCRETE	27	27	27	27	27
22 - W498 (p22)	14.2000	12.5005	16.1986	12.5018	16.1717
23 - VCG498 (p23)	-3.0000	-3.0700	-2.9801	-3.0696	-2.9806
24 - ACOXO (p24)	325.0000	289.0269	314.9958	289.2014	314.9012
25 - vf (p25) DISCRETE	3.5	3.5	3.5	3.5	3.5
26 - CDHMAT (p26) DISCRETE	2	1	2	1	2
27 - CPS (p27) DISCRETE	1	0	0	0	0
28 - kWM (p28)	46.1000	39.0027	44.9998	39.0286	44.9491
29 - W593 (p29)	14.7000	14.6006	16.4991	14.6232	16.4949
30 - W171 (p30)	2.0000	1.8000	2.1499	1.8047	2.1478
31 - VWASTE (p31)	1700.0000	1660.0247	1779.9890	1660.5113	1779.9725
32 - W598 (p32)	60.5000	57.0011	62.9999	57.0085	62.8757
33 - NG (p33) DISCRETE	2	2	2	2	2
34 - NHeIE (p34) DISCRETE	2	2	2	2	2
35 - WBP (p35)	370.0000	332.1791	364.9853	333.4049	364.6553
36 - D10C (p36)	1.0000	1.0000	1.0999	1.0003	1.0992
37 - FP (p37)	0.0790	0.0740	0.0830	0.0740	0.0828
38 - WOFH (p38)	379.2000	350.0264	381.9956	350.0337	381.3167
39 - CHMAT (p39) DISCRETE	1	0.93	1	0.93	1
40 - CBVC (p40) DISCRETE	1	0	1	0	1
41 - LCB (p41)	-10.0000	-10.0000	-9.3000	-9.9946	-9.3010
42 - PMF (p42)	1.1000	1.0500	1.1499	1.0509	1.1496
43 - PC (p43)	0.6700	0.5900	0.7382	0.5913	0.7365
44 - SELECTP (p44) DISCRETE	5	5	6	5	6
45 - SELECTG (p45) DISCRETE	4	1	1	1	1

Table 21 Design Variable Values – 4th Optimization.

Tests performed 200000
Feasible set contains: 2161
Pareto-optimal set contains: 208
Number Generator: LP-Tau Net

		Pareto-optimal set		
Criteria		**Prototype**	**Minimum**	**Maximum**
Criterion #1	ERRKW (%)	2.4861	2.2248	8.3934
Criterion #2	ERRPOWER (%)	10.0052	0.0255	9.9415
Criterion #3	ERRVOL (%)	11.7716	10.3405	34.5654
Criterion #4	ERRAREA (%)	14.3391	12.8009	38.7402
Criterion #5	ERRWEIGHT (%)	1.0124	0.1111	10.9712
Criterion #6	COST	555.7255	539.0312	549.5474
Pseudo-Criteria		**Prototype**	**Minimum**	**Maximum**
Criterion #7	f8 = CLB <= 10	9.0476	8.6234	9.4242
Criterion #8	f8 = CLB >= 7.5	9.0476	8.6234	9.4242
Criterion #9	f9 = CBT <= 3.7	2.5519	2.8002	3.2795
Criterion #10	f9 = CBT >=2.8	**2.5519**	2.8002	3.2795
Criterion #11	f10 = CDELTAL <= 65	68.2411	57.6749	64.9846
Criterion #12	f10 = CDELTAL >= 45	68.2411	57.6749	64.9846
Criterion #13	f11 = CGMB <= 0.122	0.1061	0.0901	0.1220
Criterion #14	f11 = CGMB >= 0.09	0.1061	0.0901	0.1220
Criterion #15	f5 = Eact - E	577.0966	1.3784	369.2053

Table 22 Table of Criteria – 4th Optimization.

5. Fifth Optimization Study

The main purpose of this step was to perform an investigation using Windows Random Number Generator instead of the default generator, LP Tau. The same design variable constraints (parallelepiped) and criteria constraints were used as in the fourth optimization step (See Table 12 & Table 13). Overall, 200,000 tests were conducted, 56,328 solutions did not satisfy the functional constraints, and 143,672 vectors entered the "Full Ordered Test Table". As a result, 2,169 vectors entered the truncated table. The feasible set had 2,169 vectors and the Pareto optimal set had 184 vectors. The comparison of the results of the fourth and fifth optimization runs is tabulated in Table 23. The test table and feasible set of the fifth optimization run included more vectors, but the Pareto optimal set had fewer vectors than in the fourth optimization run.

Table 24 presents the minimum and maximum criteria values of the Pareto optimal set. These results are similar to the fourth optimization results (See Table 22), and the prototype was improved. The "criterion versus criterion" graphs for this step are also presented in Appendix K with the fourth optimization graphs. The comparison of

these graphs provides evidence to this similarity. Yet again, the solutions clustered into four different zones for "Criterion 1" (ERRKW-minimized), and clustered into two different zones for "Criterion 6" (COST-minimized). The distinctive cutoff lines that reveal where the criteria constraints exist were still visible. Table 25 tabulates the maximum and minimum design variable values for the feasible and Pareto optimal set. The feasible set histograms are in Appendix M. The design variable values were evenly distributed as in the fourth optimization run. As a result, using Windows Random Number Generator instead of the default generator, LP Tau, did not change the results significantly.

	4th Optimization	5th Optimization
Tests performed	200,000	200,000
Test Table Contains	143,593	143,672
Feasible set contains	2,161	2,169
Pareto-optimal set contains	208	184
Number Generator	LP-Tau Net	Windows RNG

Table 23 Comparison of the 4th and 5th Optimizations

Tests performed 200000
Feasible set contains: 2169
Pareto-optimal set contains: 184
Number Generator: Windows RNG

			Pareto-optimal set	
Criteria		**Prototype**	**Minimum**	**Maximum**
Criterion #1	ERRKW (%)	2.4861	2.2504	8.3861
Criterion #2	ERRPOWER (%)	10.0052	0.0072	9.9763
Criterion #3	ERRVOL (%)	11.7716	13.6187	34.0599
Criterion #4	ERRAREA (%)	14.3391	17.0755	38.4115
Criterion #5	ERRWEIGHT (%)	1.0124	0.0928	11.1639
Criterion #6	COST	555.7255	539.2438	550.2092
Pseudo-Criteria		**Prototype**	**Minimum**	**Maximum**
Criterion #7	f8 = CLB <= 10	9.0476	8.6102	9.2818
Criterion #8	f8 = CLB >= 7.5	9.0476	8.6102	9.2818
Criterion #9	f9 = CBT <= 3.7	2.5519	2.8000	3.3511
Criterion #10	f9 = CBT >=2.8	**2.5519**	2.8000	3.3511
Criterion #11	f10 = CDELTAL <= 65	68.2411	59.0332	64.9777
Criterion #12	f10 = CDELTAL >= 45	68.2411	59.0332	64.9777
Criterion #13	f11 = CGMB <= 0.122	0.1061	0.0902	0.1219
Criterion #14	f11 = CGMB >= 0.09	0.1061	0.0902	0.1219
Criterion #15	f5 = Eact - E	577.0966	0.0958	397.6345

Table 24 Table of Criteria – 5th Optimization.

Tests performed 200000
Feasible set contains: 2169
Pareto-optimal set contains: 184
Number Generator: Windows RNG

		Feasible set		Pareto-optimal set	
Parameters	**Prototype**	**Minimum**	**Maximum**	**Minimum**	**Maximum**
1 - LWL (p1)	356.2500	360.0218	371.9957	360.2284	371.9353
2 - B (p2)	39.3750	39.0799	41.9993	39.4197	41.9949
3 - Ndecks (p3) DISCRETE	2	2	2	2	2
4 - CP (p4)	0.6213	0.5737	0.6400	0.5781	0.6399
5 - CX (p5)	0.8031	0.8001	0.8500	0.8011	0.8498
6 - HDKh (p6)	8.5000	8.3804	8.6998	8.3822	8.6978
7 - BILGE (p7)	5.0000	4.3001	5.2996	4.3094	5.2965
8 - HDKd (p8)	8.0500	7.9000	8.2099	7.9050	8.2084
9 - NPENG (p9) DISCRETE	2	2	2	2	2
10 - eta (p10)	0.9700	0.9600	0.9900	0.9605	0.9899
11 - NDIE (p11) DISCRETE	2	1	1	1	1
12 - NHPIE (p12) DISCRETE	1	1	2	1	2
13 - WF46 (p13)	17.6000	15.0018	18.9935	15.0018	18.9836
14 - NP (p14) DISCRETE	1	1	2	1	2
15 - DP (p15)	12.0000	11.0002	12.9989	11.0174	12.9986
16 - LS (p16)	100.5000	98.0020	101.9994	98.0087	101.9764
17 - ADB (p17)	538.9000	510.0502	560.9817	510.0541	560.6187
18 - WIC: (p18)	43.8000	36.0035	42.9970	36.0052	42.9249
19 - Nfins (p19) DISCRETE	0	0	1	0	1
20 - CSD (p20)	0.2800	0.2700	0.2880	0.2701	0.2878
21 - ASD (p21) DISCRETE	27	27	27	27	27
22 - W498 (p22)	14.2000	12.5007	16.1994	12.5148	16.1533
23 - VCG498 (p23)	-3.0000	-3.0700	-2.9801	-3.0679	-2.9801
24 - ACOXO (p24)	325.0000	289.0069	314.9824	289.4776	314.9378
25 - vf (p25) DISCRETE	3.5	3.5	3.5	3.5	3.5
26 - CDHMAT (p26) DISCRETE	2	1	2	1	2
27 - CPS (p27) DISCRETE	1	0	0	0	0
28 - kWM (p28)	46.1000	39.0107	44.9964	39.0272	44.9044
29 - W593 (p29)	14.7000	14.6011	16.4995	14.6020	16.4785
30 - W171 (p30)	2.0000	1.8001	2.1499	1.8005	2.1482
31 - VWASTE (p31)	1700.0000	1660.0291	1779.9694	1661.3043	1779.8617
32 - W598 (p32)	60.5000	57.0006	63.0000	57.0033	62.9865
33 - NG (p33) DISCRETE	2	2	2	2	2
34 - NHelE (p34) DISCRETE	2	2	2	2	2
35 - WBP (p35)	370.0000	332.2265	364.9851	332.2265	364.8961
36 - D10C (p36)	1.0000	1.0000	1.0999	1.0009	1.0991
37 - FP (p37)	0.0790	0.0740	0.0830	0.0741	0.0829
38 - WOFH (p38)	379.2000	350.0017	381.9929	350.0017	379.5752
39 - CHMAT (p39) DISCRETE	1	0.93	1	0.93	1
40 - CBVC (p40) DISCRETE	1	0	1	0	1
41 - LCB (p41)	-10.0000	-9.9996	-9.3005	-9.9978	-9.3011
42 - PMF (p42)	1.1000	1.0501	1.1500	1.0509	1.1491
43 - PC (p43)	0.6700	0.5900	0.7397	0.5913	0.7341
44 - SELECTP (p44) DISCRETE	5	5	6	5	6
45 - SELECTG (p45) DISCRETE	4	1	1	1	1

Table 25 Design Variable Values – 5^{th} Optimization.

6. Sixth Optimization Study

The main purpose of this step was to perform an investigation using "primary constraints" for criteria (See Figure 57). The same design variable constraints (parallelepiped) were used as in the fourth and fifth optimization step (See Table 12).

Analysis of the "criterion versus criterion" graphs in Appendix K for the fourth and fifth optimization step showed that the solutions clustered into four different zones for "Criterion 1" (ERRKW-minimized), and clustered into two different zones for "Criterion 6" (COST-minimized). The Pareto optimal solutions were mostly in the first zone of "Criterion 1" for values of approximately 2 to 5. The Pareto optimal solutions were also in the first zone of "Criterion 1" for values of approximately 538 to 553. Therefore, the primary criteria constraints "5" and "553" were used for "Criterion 1" and "Criterion 6" respectively. The stiffness of the primary criteria constraint of "Criterion 2" (ERRPOWER-minimized) was also increased. Again, no negative values were allowed for the ERRVOL, ERRAREA, and ERRWEIGHT (See Table 13 & Figure 57).

The default generator, LP Tau, was used for this step. In this step, 500,000 tests were conducted instead of 200,000 tests. 141,006 solutions did not satisfy the functional constraints, 355,422 solutions did not satisfy the "primary criteria constraints". Hence, 3,572 vectors entered the "Full Ordered Test Table". After analysis of the test table, the same pseudo-criteria constraints were used as in the fourth and fifth optimization step with the exception of "f5 = Eact – E". The stiffness of the pseudo-criterion constraint of "f5 = Eact – E" was increased (See Table 13). As a result of the pseudo-criteria constraints, 627 vectors entered the truncated table. The feasible set had 627 vectors and the Pareto optimal set had 138 vectors.

Table 26 shows the comparison of the minimum and maximum criteria values of the Pareto optimal set and the criteria values of the prototype. The improvement of the prototype is obvious. The "criterion versus criterion" graphs for this step are presented in Appendix L. The vectors presented in these graphs were sparsely distributed, since only 3,572 vectors entered the "Full Ordered Test Table". The maximum and minimum design variable values for the feasible and Pareto optimal set are in Table 27. The feasible set histograms are in Appendix M. The design variable values were evenly distributed as in

the fourth and fifth optimization run. Only the "Design Variable 19" had a different distribution.

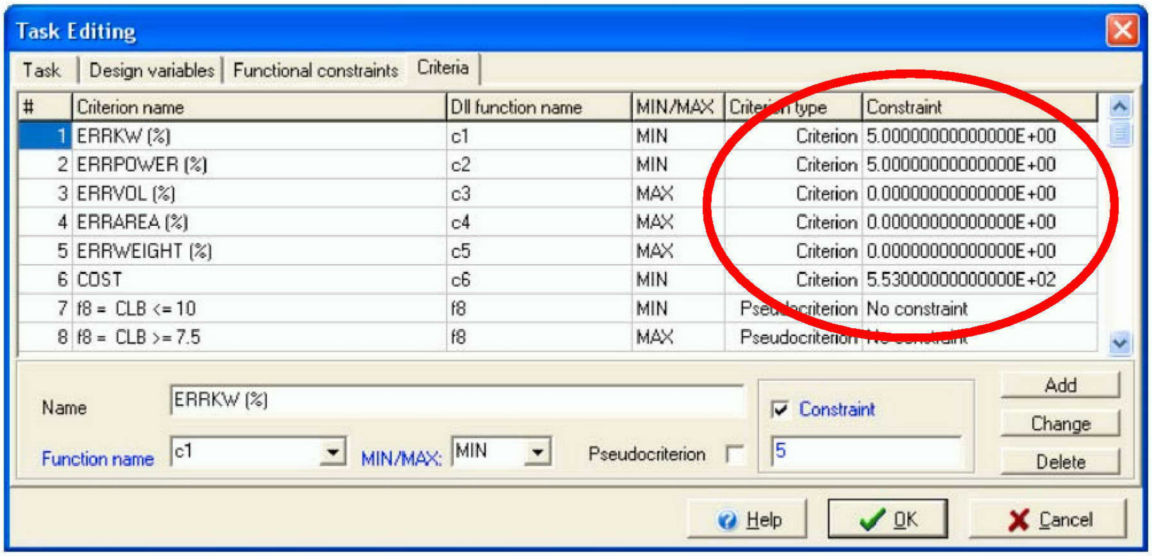

Figure 57 Primary Constraints for Criteria.

Tests performed: 500000
Feasible set contains: 627
Pareto-optimal set contains: 138
Number Generator: LP-Tau Net

Criteria		Prototype	Pareto-optimal set Minimum	Maximum
Criterion #1	**ERRKW (%)**	2.4861	2.2248	4.7020
Criterion #2	**ERRPOWER (%)**	10.0052	0.0009	4.9669
Criterion #3	**ERRVOL (%)**	11.7716	11.9537	32.2442
Criterion #4	**ERRAREA (%)**	14.3391	14.9180	36.3048
Criterion #5	**ERRWEIGHT (%)**	1.0124	0.0785	10.6806
Criterion #6	**COST**	555.7255	540.1160	549.3542
Pseudo-Criteria		**Prototype**	**Minimum**	**Maximum**
Criterion #7	**f8 = CLB <= 10**	9.0476	8.6234	9.2231
Criterion #8	**f8 = CLB >= 7.5**	9.0476	8.6234	9.2231
Criterion #9	**f9 = CBT <= 3.7**	2.5519	2.8045	3.2262
Criterion #10	**f9 = CBT >=2.8**	**2.5519**	2.8045	3.2262
Criterion #11	**f10 = CDELTAL <= 65**	68.2411	59.5658	64.9889
Criterion #12	**f10 = CDELTAL >= 45**	68.2411	59.5658	64.9889
Criterion #13	**f11 = CGMB <= 0.122**	0.1061	0.0902	0.1215
Criterion #14	**f11 = CGMB >= 0.09**	0.1061	0.0902	0.1215
Criterion #15	**f5 = Eact - E**	577.0966	0.5992	198.3515

Table 26 Table of Criteria – 6th Optimization.

Tests performed 500000
Feasible set contains: 627
Pareto-optimal set contains: 138
Number Generator: LP-Tau Net

		Feasible set		Pareto-optimal set	
Parameters	**Prototype**	**Minimum**	**Maximum**	**Minimum**	**Maximum**
1 - LWL (p1)	356.2500	360.0047	371.9783	360.5236	371.8808
2 - B (p2)	39.3750	39.1776	41.9998	39.8194	41.9998
3 - Ndecks (p3) DISCRETE	2	2	2	2	2
4 - CP (p4)	0.6213	0.5779	0.6400	0.5954	0.6400
5 - CX (p5)	0.8031	0.8001	0.8500	0.8003	0.8499
6 - HDKh (p6)	8.5000	8.3807	8.6997	8.3807	8.6969
7 - BILGE (p7)	5.0000	4.3004	5.2964	4.3009	5.2958
8 - HDKd (p8)	8.0500	7.9009	8.2098	7.9009	8.2097
9 - NPENG (p9) DISCRETE	2	2	2	2	2
10 - eta (p10)	0.9700	0.9600	0.9900	0.9601	0.9890
11 - NDIE (p11) DISCRETE	2	1	1	1	1
12 - NHPIE (p12) DISCRETE	1	1	2	1	2
13 - WF46 (p13)	17.6000	15.0003	18.9945	15.0213	18.8997
14 - NP (p14) DISCRETE	1	1	2	1	2
15 - DP (p15)	12.0000	11.0004	12.9957	11.0025	12.9807
16 - LS (p16)	100.5000	98.0008	101.9895	98.0008	101.9615
17 - ADB (p17)	538.9000	510.0078	560.9982	510.0078	560.9982
18 - WIC: (p18)	43.8000	36.0026	42.9956	36.0756	42.8832
19 - Nfins (p19) DISCRETE	0	1	1	1	1
20 - CSD (p20)	0.2800	0.2700	0.2880	0.2705	0.2880
21 - ASD (p21) DISCRETE	27	27	27	27	27
22 - W498 (p22)	14.2000	12.5007	16.1733	12.5018	16.1508
23 - VCG498 (p23)	-3.0000	-3.0700	-2.9803	-3.0682	-2.9803
24 - ACOXO (p24)	325.0000	289.0173	314.9012	289.0747	314.9012
25 - vf (p25) DISCRETE	3.5	3.5	3.5	3.5	3.5
26 - CDHMAT (p26) DISCRETE	2	1	2	1	2
27 - CPS (p27) DISCRETE	1	0	0	0	0
28 - kWM (p28)	46.1000	39.0239	44.9933	39.0239	44.9919
29 - W593 (p29)	14.7000	14.6064	16.4970	14.6154	16.4784
30 - W171 (p30)	2.0000	1.8006	2.1490	1.8006	2.1490
31 - VWASTE (p31)	1700.0000	1660.1092	1779.4212	1661.1046	1778.3429
32 - W598 (p32)	60.5000	57.0079	62.9902	57.0576	62.9636
33 - NG (p33) DISCRETE	2	2	2	2	2
34 - NHelE (p34) DISCRETE	2	2	2	2	2
35 - WBP (p35)	370.0000	335.9668	364.9681	335.9668	364.9541
36 - D10C (p36)	1.0000	1.0001	1.0996	1.0003	1.0975
37 - FP (p37)	0.0790	0.0740	0.0830	0.0740	0.0817
38 - WOFH (p38)	379.2000	350.0337	381.9823	350.0337	381.6412
39 - CHMAT (p39) DISCRETE	1	0.93	1	0.93	1
40 - CBVC (p40) DISCRETE	1	0	1	0	1
41 - LCB (p41)	-10.0000	-9.9992	-9.3001	-9.9898	-9.3001
42 - PMF (p42)	1.1000	1.0500	1.1500	1.0500	1.1498
43 - PC (p43)	0.6700	0.5900	0.7108	0.5913	0.7048
44 - SELECTP (p44) DISCRETE	5	5	6	5	6
45 - SELECTG (p45) DISCRETE	4	1	1	1	1

Table 27 Design Variable Values – 6th Optimization.

C. SUMMARY OF RESULTS

In this study, the "MIT Functional Ship Design Synthesis Model" was investigated using the Parameter Space Investigation (PSI) technique. The model was previously written in Mathcad programming language. It was not formulated for the Parameter Space Investigation (PSI) technique. The feasible solutions satisfy all requirement constraints and five main error verifications. These errors were the propulsion power error, the electrical power error, the volume error, the area error, and the weight error. All errors must be reasonably small. The propulsion power error and the electrical power error must be strictly greater than or equal to zero. The error verification process was performed manually and step-by-step. In other words, these five errors were the five main performance criteria for this model, which was optimized by trying different values for the parameters recursively.

During the modification of the model for the Parameter Space Investigation (PSI) technique, all errors were represented in percentages. For example, the percentage volume error was "ERRVOL = 100 × (VTA – VTR)/VTR", where "VTR" was the total required volume, and "VTA" was the total actual volume. A very simplified cost model (lead-ship end cost only) was added as the sixth performance criterion, using the former version of the model.

The modification process required complete designation of the "design variables", the "functional relations" and "functional constraints", and the "performance criteria" and "criteria constraints" to portray the multi-criteria optimization problem for the PSI method. This designation resulted in six criteria and eleven functional relations which were subject to sixteen different functional constraints. Nine of the functional constraints were not rigid, and their functional relations were treated as pseudo-criteria. There were forty-five design parameters to optimize. Sixteen of them were discrete variables.

Overall, six optimization studies were conducted for this model. In the first optimization study, the initial design variable space (parallelepiped) was determined, and a "global search" for the feasible solutions was performed using flexible criteria and pseudo-criteria constraints. The prototype could not be improved in the first optimization; hence, a new parallelepiped was defined utilizing the "Tables" and "Histograms and

Graphs" options of MOVI software. The stiffness of criteria (and pseudo-criteria) constraints was increased as well. The second optimization study was performed. After this second "global search" in the new design variable space, the results were superior to the first optimization results, but did not improve upon the prototype. Therefore, the stiffness of criteria (and pseudo-criteria) constraints was increased again, and another "global search" was conducted in the third design variable space, which was defined after the analysis of the first two optimization results. Finally, the prototype was improved. Only three Pareto optimal solutions were obtained as a result of three optimization runs of 200,000 tests each. This fact illustrates the complexity of improving on the prototype.

Once the results of the first three optimization studies were analyzed, the problem statement was corrected by reducing the number of design variables and redefining the design variable constraints. In the fourth optimization study, another search for the optimal solutions was conducted in this fourth parallelepiped. The results were better than the third optimization results, and the prototype was improved.

The default generator, LP Tau, was used for the first four optimization studies. In the fifth optimization study an investigation was conducted using Windows Random Number Generator instead of the default generator, LP Tau. The same design variable constraints (parallelepiped) and criteria constraints were used as in the fourth optimization step. No significant changes in the results were observed, despite the use of a different number generator.

In the sixth optimization study an investigation was performed using "primary constraints" for criteria. The same design variable constraints (parallelepiped) were used as in the fourth and fifth optimization steps. Due to the primary criteria constraints, fewer vectors entered the "Full Ordered Test Table". The results were superior to the fourth and fifth optimization results, and the prototype was further improved. The summary of the results for each step is presented in Table 28. Comparison of maximum and minimum criteria values (Pareto optimal set) for each optimization step is tabulated in Table 29.

A MATLAB code "shiptest.m" that directly interacts with the MATLAB model was written for result validation (See Appendix G). First, using the "Perform One Test" menu, values of the selected design variable vector and corresponding values of

functional relations and criteria were exported to Microsoft Excel. The code, "shiptest.m", takes this exported data and sends the selected design variable vector directly to the MATLAB model. After computation of the values of functional relations and criteria, the test code calculates the error between the MOVI and direct MATLAB results. Finally, the test code exports the comparison of the results to Microsoft Excel. Repeating this test for different vectors demonstrated that there were no or negligible floating point errors.

	1st Optimization	2nd Optimization	3rd Optimization	4th Optimization	5th Optimization	6th Optimization
Tests performed	200,000	200,000	200,000	200,000	200,000	500,000
Test Table Contains	10,025	11,331	18,553	143,593	143,672	3,572
Feasible set contains	7	9	3	2,161	2,169	627
Pareto-optimal set contains	7	8	3	208	184	138
Number Generator	LP-Tau Net	LP-Tau Net	LP-Tau Net	LP-Tau Net	Windows RNG	LP-Tau Net

Table 28 Results for Each Optimization.

			1st Optimization		2nd Optimization		3rd Optimization	
Criteria		**Prototype**	**Minimum**	**Maximum**	**Minimum**	**Maximum**	**Minimum**	**Maximum**
Criterion #1	ERRKW (%)	2.4861	0.7701	67.5170	6.0586	43.5823	6.2190	40.0043
Criterion #2	ERRPOWER (%)	10.0052	9.5599	49.7089	1.6650	42.8981	9.9123	12.7196
Criterion #3	ERRVOL (%)	11.7716	-6.7187	27.7329	5.1115	34.0227	10.9841	27.6015
Criterion #4	ERRAREA (%)	14.3391	-8.4763	32.2181	6.1515	37.8876	13.6040	31.2549
Criterion #5	ERRWEIGHT (%)	1.0124	-42.8251	-16.8812	-19.6645	-3.3062	1.9407	3.1097
Criterion #6	COST	555.7255	548.3922	593.6998	542.6230	581.4986	545.2049	558.6413
Pseudo-Criteria		**Prototype**	**Minimum**	**Maximum**	**Minimum**	**Maximum**	**Minimum**	**Maximum**
Criterion #7	f8 = CLB <= 10	9.0476	7.8701	9.0826	8.0826	9.0950	8.9050	9.0206
Criterion #8	f8 = CLB >= 7.5	9.0476	7.8701	9.0826	8.0826	9.0950	8.9050	9.0206
Criterion #9	f9 = CBT <= 3.7	2.5519	2.8647	3.6964	2.7745	3.0940	2.7215	2.9267
Criterion #10	f9 = CBT >=2.8	**2.5519**	2.8647	3.6964	2.7745	3.0940	2.7215	2.9267
Criterion #11	f10 = CDELTAL <= 65	68.2411	47.1992	65.8392	53.5285	65.2266	62.9397	64.2897
Criterion #12	f10 = CDELTAL >= 45	68.2411	47.1992	65.8392	53.5285	65.3906	62.9397	64.2897
Criterion #13	f11 = CGMB <= 0.122	0.1061	0.0890	0.1135	0.0840	0.1193	0.0815	0.1161
Criterion #14	f11 = CGMB >= 0.09	0.1061	0.0890	0.1135	0.0840	0.1193	0.0815	0.1161
Criterion #15	f5 = Eact - E	577.0966	663.5402	1223.3569	94.9729	1261.9762	67.2061	379.4735

			4th Optimization		5th Optimization		6th Optimization	
Criteria		**Prototype**	**Minimum**	**Maximum**	**Minimum**	**Maximum**	**Minimum**	**Maximum**
Criterion #1	ERRKW (%)	2.4861	2.2248	8.3934	2.2504	8.3861	2.2248	4.7020
Criterion #2	ERRPOWER (%)	10.0052	0.0255	9.9415	0.0072	9.9763	0.0009	4.9669
Criterion #3	ERRVOL (%)	11.7716	10.3405	34.5654	13.6187	34.0599	11.9537	32.2442
Criterion #4	ERRAREA (%)	14.3391	12.8009	38.7402	17.0755	38.4115	14.9180	36.3048
Criterion #5	ERRWEIGHT (%)	1.0124	0.1111	10.9712	0.0928	11.1639	0.0785	10.6806
Criterion #6	COST	555.7255	539.0312	549.5474	539.2438	550.2092	540.1160	549.3542
Pseudo-Criteria		**Prototype**	**Minimum**	**Maximum**	**Minimum**	**Maximum**	**Minimum**	**Maximum**
Criterion #7	f8 = CLB <= 10	9.0476	8.6234	9.4242	8.6102	9.2818	8.6234	9.2231
Criterion #8	f8 = CLB >= 7.5	9.0476	8.6234	9.4242	8.6102	9.2818	8.6234	9.2231
Criterion #9	f9 = CBT <= 3.7	2.5519	2.8002	3.2795	2.8000	3.3511	2.8045	3.2262
Criterion #10	f9 = CBT >=2.8	**2.5519**	2.8002	3.2795	2.8000	3.3511	2.8045	3.2262
Criterion #11	f10 = CDELTAL <= 65	68.2411	57.6749	64.9846	59.0332	64.9777	59.5658	64.9889
Criterion #12	f10 = CDELTAL >= 45	68.2411	57.6749	64.9846	59.0332	64.9777	59.5658	64.9889
Criterion #13	f11 = CGMB <= 0.122	0.1061	0.0901	0.1220	0.0902	0.1219	0.0902	0.1215
Criterion #14	f11 = CGMB >= 0.09	0.1061	0.0901	0.1220	0.0902	0.1219	0.0902	0.1215
Criterion #15	f5 = Eact - E	577.0966	1.3784	369.2053	0.0958	397.6345	0.5992	198.3515

Table 29 Maximum/Minimum Criteria Values (Pareto Optimal Set) for Each Optimization.

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VI. CONCLUSIONS AND RECOMMENDATIONS

A. CONCLUSIONS

This Thesis demonstrated that the Parameter Space Investigation (PSI) technique can be implemented in the naval ship design environment to solve optimization problems involving systems with multiple and often contradictory criteria. The PSI method is implemented with a software package called MOVI (Multi-criteria Optimization and Vector Identification). Two marine/naval engineering design optimization models were investigated to verify the fact that the PSI technique along with the MOVI software can be used to resolve these contradictions, which has been a challenge for marine/naval engineering design studies for many years.

The first example was a bulk carrier design model that was previously studied with other optimization techniques such as "weighted sum", "minimum-maximum", "weighted minimum maximum", "goal programming", and "nearest to the utopian design" methods. It was selected due to its relatively small dimensionality and the availability of existing studies. This model was utilized in order to demonstrate and validate the features of the Parameter Space Investigation technique.

The second example was more realistic and was based on the "MIT Functional Ship Design Synthesis Model" with a greater number of parameters, criteria, and functional constraints. This model was utilized in order to demonstrate and validate that the Parameter Space Investigation (PSI) technique can lead to a large design parameter space exploration with minimum computational effort.

B. RECOMMENDATIONS

The two examples studied in this Thesis were not formulated for the Parameter Space Investigation technique. Therefore, these models are modified not only for MATLAB, but also for the PSI method. Other programming languages could be used instead of MATLAB, but, for further studies, it is recommended to comprehend the definitions of "design variable", the "functional relation" and "functional constraints", and the "performance criterion" and "criterion constraints" before starting the modification of the model.

It is crucial to be sure that the modified model is debugged enough to begin the optimization process. In other words, the model must be reliable. It is also practical to have a list of design variables, functional relations and "functional constraints, performance criteria" and criteria constraints. It must be specified whether the design variables are continuous or discrete.

The "prototype" is the desired design or the existing design that needs to be improved. If it is known that a prototype exists, it will be uncomplicated to define the boundaries of the parameters (the design variable constraints). Recall that the general strategy to determine the initial parallelepiped is to put the prototype in the center of it, unless the design variable constraints are already given.

The functional relations that do not have rigid functional constraints may be assumed to be "pseudo-criteria" at the beginning of the analysis. The functional relations must be minimized for the upper functional constraint, and maximized for the lower functional constraint. This process ensures that more vectors enter the test table. During the analysis of the test table the appropriate values of pseudo-criteria constraints can be introduced in place of the functional constraints.

It is highly recommended to execute MOVI in parallel mode if the number of design variables is large. MOVI provides this opportunity to run the optimization process simultaneously on many computers. The "Combine Solutions" menu is used to unite the separated results. This procedure saves a lot of time.

The optimization problems with less then nine design variables can be solved using the "Educational" version of this software (MOVI 1.3). The full edition MOVI 1.3 package should be used to optimize problems with greater than eight design variables.

APPENDIX A. BULK CARRIER DESIGN OPTIMIZATION MODEL

Formulation of Multicriterion Design Optimization Problems for Solution With Scalar Numerical Optimization Methods

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(Ship parametric design model taken from SEN, P., AND YANG, J.B. 1998 Multiple Criteria Decision Support in Engineering Design, Springer, London.)

1) transportation cost = **annual costs**/**annual cargo** (£/t)

2) light ship weight = $W_s + W_o + W_m$ **(t)**

3) **annual cargo** = **cargo DWT· RTPA** (t/yr)

(**RTPA** = Round Trips Per Year)

annual costs = **capital costs** + **running costs** + **voyage costs**

capital costs = 0.2 **ship cost**

ship cost = $1.3\,(2{,}000\, W_s^{0.85} + 3{,}500\, W_o + 2{,}400\, P^{0.8})$

W_s = steel weight = $0.034\, L^{1.7}\, B^{0.7}\, D^{0.4}\, C_B^{0.5}$

W_o = outfit weight = $1.0\, L^{0.8}\, B^{0.6}\, D^{0.3}\, C_B^{0.1}$

W_m = machinery weight = $0.17\, P^{0.9}$

P = power = **displacement**$^{2/3}\, V_k^3 / (\mathbf{a} + \mathbf{b}\, F_n)$

displacement = $1.025\, L\, B\, T\, C_B$

Froude number = $F_n = V/(gL)^{0.5}$

$V = 0.5144\, V_k$ m/s;

$g = 9.8065$ m/s^2

a and **b** are quadratic functions of C_B to implement the **Admiralty Coefficient** based on speed in knots,

$$\mathrm{AC} = \mathbf{a} + \mathbf{b}\, F_n$$

$$\mathbf{a} = 4{,}977.06\, C_B^2 - 8{,}105.61\, C_B + 4{,}456.51$$

$$\mathbf{b} = -\,10{,}847.2\, C_B^2 + 12{,}817\, C_B - 6{,}960.32$$

$$\text{running costs} = 40{,}000\ \text{DWT}^{0.3}$$

$$\text{DWT} = \text{deadweight} = \text{displacement} - \text{light ship}$$

$$\text{voyage costs} = (\text{fuel cost} + \text{port cost}) \cdot \text{RTPA}$$

$$\text{fuel cost} = 1.05\ \text{daily consumption} \cdot \text{sea days} \cdot \text{fuel price}$$

$$\text{daily consumption} = 0.19\ P \cdot 24/1{,}000 + 0.2$$

$$\text{sea days} = \text{round trip miles}/24 V_k$$

$$\text{round trip miles} = 5{,}000\ \text{(nm)}$$

$$\text{fuel price} = 100\ \text{(£/t)}$$

$$\text{port cost} = 6.3\ \text{DWT}^{0.8}$$

$$\text{RTPA} = \text{round trips per year} = 350/(\text{sea days} + \text{port days})$$

$$\text{port days} = 2[(\text{cargo DWT}/\text{handling rate}) + 0.5]$$

$$\text{cargo DWT} = \text{DWT} - \text{fuel carried} - \text{miscellaneous DWT}$$

$$\text{fuel carried} = \text{daily consumption} \cdot (\text{sea days} + 5)$$

$$\text{miscellaneous DWT} = 2.0\ \text{DWT}^{0.5}$$

$$\text{handling rate} = 8{,}000\ \text{(t/day)}$$

$$\boxed{GM_T = KB + BM_T - KG \geq 0.07\ B}$$

vertical center of buoyancy = $KB = 0.53\ T$

metacentric radius = $BM_T = (0.085\ C_B - 0.002)B^2/(T\ C_B)$

vertical center of gravity = $KG = 1.0 + 0.52\ D$

APPENDIX B. MATLAB CODE OF BULK CARRIER DESIGN OPTIMIZATION MODEL

Ship.m

```
function [c1,c2,c3,f1,f2,f3,f4,f5,f6,f7,f8] = Ship(p1,p2,p3,p4,p5,p6)
% NUMERICAL EXAMPLE CASE 1
% c1 ... c3     = Output criteria values
% f1 ... f8     = Output function values
% p1 ... p6     = Input parameters values
% Kivanc Ali ANIL, 2004
% constants used
g   = 9.8065;                                      % (m/s^2)
rtm = 5000;                                        % round trip miles (nm)
fp  = 100;                                         % fuel price(£/t)
hr  = 8000;                                        % handling rate (t/day)
% assign variables
L   = p1;                                          % length (m)  L <= 274.32 m
B   = p2;                                          % beam (m)
D   = p3;                                          % depth (m)
T   = p4;                                          % draft (m)
CB  = p5;                                          % block coefficient, 0.63<=CB<=0.75
Vk  = p6;                                          % speed (knots),  14 <= Vk <= 18
% perform computations
dsp = 1.025*L*B*T*CB;                              % displacement (t)
V   = 0.5144*Vk;                                   % speed (m/s)
Fn  = V/((g*L)^0.5);                               % Froude number
a   = 4977.06*CB^2 - 8105.61*CB + 4456.51;
b   = -10847.2*CB^2 + 12817*CB - 6960.32;
P   = (dsp^(0.66666666666667))*(Vk^3) /(a + b*Fn); % power (Characteristics)
Ws  = 0.034*(L^1.7)*(B^0.7)*(D^0.4)*(CB^0.5);      % steel weight
Wo  = 1.0 * (L^0.8)*(B^0.6)*(D^0.3)*(CB^0.1);      % outfit weight
Wm  = 0.17*P^0.9 ;                                 % machinery weight
sc  = 1.3*(2000*Ws^0.85 + 3500*Wo + 2400*P^0.8);   % ship cost (£/t)
cc  = 0.2*sc ;                                     % capital costs (£/t)
lsw = Ws + Wo + Wm ;                               % light ship weight **** Min
DWT = dsp - lsw ;                                  % deadweight
rc  = 40000*DWT^0.3 ;                              % running costs (£/t)
dc  = 0.19*P*0.024+0.2;                            % daily consumption
sd  = rtm/(24*Vk);                                 % sea days
fc  = 1.05 * dc * sd * fp ;                        % fuel cost(£/t)
pc  = 6.3*DWT^0.8 ;                                % port cost (£/t)
fcr = dc * (sd + 5);                               % fuel carried
mDWT= 2.0*DWT^0.5 ;                                % miscellaneous DWT
cDWT= DWT - fcr - mDWT;                            % cargo DWT
pd  = 2*((cDWT/hr) + 0.5);                         % port days
RTPA= 350/(sd + pd);                               % round trips per year
vc  = (fc + pc) * RTPA;                            % voyage costs (£/t)
ac  = cc + rc + vc ;                               % annual costs(£/t)
acrg= cDWT * RTPA ;                                % annual cargo (t/yr)**** Max
trc = ac/acrg ;                                    % transportation cost (£/t)**** Min
KB  = 0.53*T;                                      % vertical center of buoyancy
BMT = ((0.085*CB - 0.002)*B^2) /(T*CB );           % metacentric radius
KG  = 1.0 + 0.52*D ;                               % vertical center of gravity
GMT = KB + BMT - KG ;
% criteria values
c1  = trc;                                         % transportation cost (£/t) **** Min
c2  = lsw;                                         % light ship weight **** Min
c3  = acrg;                                        % annual cargo (t/yr)**** Max
% functions values
f1  = L/B;                                         % L/B >= 6
f2  = L/D;                                         % L/D <= 15
f3  = L/T;                                         % L/T <= 19
f4  = T - 0.45*DWT^0.31;                           % T - 0.45*DWT^0.31 <= 0
f5  = T - 0.7*D - 0.7 ;                            % T - 0.7*D - 0.7 <= 0
f6  = DWT;                                         % 25,000 <= DWT <= 500,000
f7  = Fn;                                          % Fn <= 0.32
f8  = GMT -0.07*B ;                                % GMT -0.07*B >= 0
% REFERENCES:
% [1] movi_oscillator.m (MATLAB m-file) (STATNIKOV R.B.)
% [2] STATNIKOV R.B. 2003, MOVI 1.3 Software Package User's Manual.
% [3] PARSONS M.G., SCOTT R.L. March 2004, Formulation of Multicriterion Design
%     Optimization Problems for Solution With Scalar Numerical Optimization Methods,
%     Journal of Ship Research, Vol.48, No.1
```

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APPENDIX C. VISUAL C++ FILE TO CREATE MATLAB MOVI INTERFACE (BULK CARRIER DESIGN OPTIMIZATION MODEL)

```
Ship CPP file
#include "stdafx.h"
#include "Ship.h"
#include "math.h"
#include "malloc.h"
#include <string.h>
#include "engine.h"

double crits[3];
double funcs[8];
Engine *ep;
bool flag;


/*************************************************************************************
Defines the entry point for the DLL application.
You should place all important initialization and prologue/epilogue code
here
*************************************************************************************/

BOOL APIENTRY DllMain( HANDLE hModule,
                       DWORD  ul_reason_for_call,
                       LPVOID lpReserved
                                        )
{
  switch (ul_reason_for_call) {
               case DLL_PROCESS_ATTACH:{
                      flag = true;
                      break;
               }
               case DLL_THREAD_ATTACH:{break;}
               case DLL_THREAD_DETACH:{break;}
               case DLL_PROCESS_DETACH:      {
                      engClose(ep);
                      flag = true;
                      break;
               }
   }
    return TRUE;
}

/*************************************************************************************
Initialization function
*************************************************************************************/

Ship_API int WINAPI Init(WORD &NPar, WORD &NFun, WORD &NCrit, char *S)
{
       // NPar - the number of design variables in the problem;
       NPar = 6;
       // NFun - the number of functional relations;
       NFun = 8;
       // NCrit - the number of criteria;
       NCrit= 3;
       // S - a string containing identifiers of the functions used to calculate criteria
       // and functional relations
       strcpy(S,"f1,f2,f3,f4,f5,f6,f7,f8,c1,c2,c3;");


       return 0;
}

/*************************************************************************************
Functional relations functions
*************************************************************************************/

Ship_API double WINAPI f1(double Alpha[])
{
    int res=1;
       mxArray *T = NULL, *result = NULL;

       double init[6] = {Alpha[1],Alpha[2],Alpha[3],Alpha[4],Alpha[5],Alpha[6]};
        // Initial values for optimization parameters
```

```
        mxArray *p1= NULL,*p2= NULL,*p3= NULL,*p4= NULL,*p5= NULL,*p6= NULL;
         // C  variables that will be sent to Matlab

        /* Start the MATLAB engine locally by executing the string   */
        if (flag) {
                if (!(ep = engOpen(NULL))) {
                        fprintf(stderr, "\nCan't start MATLAB engine\n");
                        return -1;
                }
                flag = false;
        }

        /*
         * Send data to MATLAB, start simulation, and get results back.
         */

        /*  Create a variable for our data */
                p1=mxCreateScalarDouble(init[0]);
                p2=mxCreateScalarDouble(init[1]);
                p3=mxCreateScalarDouble(init[2]);
                p4=mxCreateScalarDouble(init[3]);
                p5=mxCreateScalarDouble(init[4]);
                p6=mxCreateScalarDouble(init[5]);


    /* Place the variables into the MATLAB workspace */
                engPutVariable(ep, "p1", p1);
                engPutVariable(ep, "p2", p2);
                engPutVariable(ep, "p3", p3);
                engPutVariable(ep, "p4", p4);
                engPutVariable(ep, "p5", p5);
                engPutVariable(ep, "p6", p6);

     /* Run matlab model Ship; */

     engEvalString(ep,"[c1v,c2v,c3v,f1v,f2v,f3v,f4v,f5v,f6v,f7v,f8v]=
Ship(p1,p2,p3,p4,p5,p6);");

     /* Get result of computation */

    result = engGetVariable(ep,"c1v");
        crits[0] = *(mxGetPr(result));
    result = engGetVariable(ep,"c2v");
        crits[1] = *(mxGetPr(result));
    result = engGetVariable(ep,"c3v");
        crits[2] = *(mxGetPr(result));
    result = engGetVariable(ep,"f1v");
        funcs[0] = *(mxGetPr(result));
    result = engGetVariable(ep,"f2v");
        funcs[1] = *(mxGetPr(result));
    result = engGetVariable(ep,"f3v");
        funcs[2] = *(mxGetPr(result));
    result = engGetVariable(ep,"f4v");
        funcs[3] = *(mxGetPr(result));
    result = engGetVariable(ep,"f5v");
        funcs[4] = *(mxGetPr(result));
    result = engGetVariable(ep,"f6v");
        funcs[5] = *(mxGetPr(result));
    result = engGetVariable(ep,"f7v");
        funcs[6] = *(mxGetPr(result));
    result = engGetVariable(ep,"f8v");
        funcs[7] = *(mxGetPr(result));


        /* We're done! Free memory. */

        mxDestroyArray(p1);
        mxDestroyArray(p2);
        mxDestroyArray(p3);
        mxDestroyArray(p4);
        mxDestroyArray(p5);
        mxDestroyArray(p6);
        mxDestroyArray(result);
        mxDestroyArray(T);
        return (funcs[0]);
}

Ship_API double WINAPI f2(double Alpha[])
{
        return (funcs[1]);
```

```
}

Ship_API double WINAPI f3(double Alpha[])
{
	return (funcs[2]);
}

Ship_API double WINAPI f4(double Alpha[])
{
	return (funcs[3]);
}

Ship_API double WINAPI f5(double Alpha[])
{
	return (funcs[4]);
}

Ship_API double WINAPI f6(double Alpha[])
{
	return (funcs[5]);
}

Ship_API double WINAPI f7(double Alpha[])
{
	return (funcs[6]);
}

Ship_API double WINAPI f8(double Alpha[])
{
	return (funcs[7]);
}


/*************************************************************************************
Criteria functions
*************************************************************************************/

Ship_API double WINAPI c1(double Alpha[])
{
	return (crits[0]);
}

Ship_API double WINAPI c2(double Alpha[])
{
	return (crits[1]);
}

Ship_API double WINAPI c3(double Alpha[])
{
	return (crits[2]);
}

/REFERENCES:
[1] OscTask (CPP file) (STATNIKOV R.B.)
[2] STATNIKOV R.B. 2003, MOVI 1.3 Software Package User's Manual./
```

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APPENDIX D. VISUAL C++ FILE TO CREATE DLL AS A MODEL (BULK CARRIER DESIGN OPTIMIZATION MODEL)

Ship CPP file

```
#include "stdafx.h"
#include "Ship.h"
#include "math.h"
#include "malloc.h"

/************************************************************************************
Some useful macro definitions
************************************************************************************/

double crits[3];
double funcs[8];

/************************************************************************************
Defines the entry point for the DLL application.
You should place all important initialization and prologue/epilogue code here
************************************************************************************/

BOOL APIENTRY DllMain( HANDLE hModule,
                                        DWORD  ul_reason_for_call,
                                        LPVOID lpReserved
                                        )
{
        switch (ul_reason_for_call)
        {
        case DLL_PROCESS_ATTACH:
        case DLL_THREAD_ATTACH:
        case DLL_THREAD_DETACH:
        case DLL_PROCESS_DETACH:
                break;
        }
        return TRUE;
}

/************************************************************************************
Initialization function
************************************************************************************/
SHIP_API int WINAPI Init(WORD &NPar, WORD &NFun, WORD &NCrit, char *S)
{
        // NPar - the number of design variables in the problem;
        NPar = 6;
        // NFun - the number of functional relations;
        NFun = 8;
        // NCrit - the number of criteria;
        NCrit= 3;
        // S -   a string containing identifiers of the functions used to calculate
criteria
        // and functional relations
        strcpy(S,"f1,f2,f3,f4,f5,f6,f7,f8,c1,c2,c3;");


        return 0;
}

/************************************************************************************
Functional relations functions
************************************************************************************/
SHIP_API double WINAPI f1(double Alpha[])
{


        const double g =9.8065;                         // (m/s^2)
        const double rtm = 5000.0;                      // round trip miles (nm)
        const double fp  = 100.0;                       // fuel price(£/t)
        const double hr  = 8000.0;                      // handling rate (t/day)

        // assign variables

        double L  = Alpha[1];                           // length (m)
        double B  = Alpha[2];                           // beam (m)
        double D  = Alpha[3];                           // depth (m)
        double T  = Alpha[4];                           // draft (m)
        double CB = Alpha[5];    // block coefficient, 0.63 <= CB <= 0.75
```

```
        double Vk = Alpha[6];    // speed (knots),       14 <= Vk <= 18

        // perform computations

        double dsp = 1.025*L*B*T*CB;                 // displacement (t)
        double V   = 0.5144*Vk;                      // speed (m/s)
        double Fn  = V/(pow((g*L),0.5));             // Froude number
        double a   = 4977.06*pow(CB,2) - 8105.61*CB + 4456.51;
        double b   = -10847.2*pow(CB,2) + 12817*CB - 6960.32; // Admiralty Coefficient
        double P   = (pow(dsp,(0.666666666666667)))*(pow(Vk,3)) /(a + b*Fn);    // power
        double Ws  = 0.034*(pow(L,1.7))*(pow(B,0.7))*(pow(D,0.4))*(pow(CB,0.5));
        double Wo  = 1.0 * (pow(L,0.8))*(pow(B,0.6))*(pow(D,0.3))*(pow(CB,0.1));
        double Wm  = 0.17*pow(P,0.9);                // machinery weight
        double sc  = 1.3*(2000*pow(Ws,0.85) + 3500*Wo + 2400*pow(P,0.8));   // ship cost
        double cc  = 0.2*sc;                         // capital costs (£/t)
        double lsw = Ws + Wo + Wm;                   // light ship weight **** Minimize
        double DWT = dsp - lsw;                      // deadweight
        double rc  = 40000*pow(DWT,0.3);             // running costs (£/t)
        double dc  = 0.19*P*0.024+0.2;               // daily consumption
        double sd  = rtm/(24*Vk);                    // sea days
        double fc  = 1.05 * dc * sd * fp;            // fuel cost(£/t)
        double pc  = 6.3*pow(DWT,0.8);               // port cost (£/t)
        double fcr = dc * (sd + 5);                  // fuel carried
        double mDWT= 2.0*pow(DWT,0.5);               // miscellaneous DWT
        double cDWT= DWT - fcr - mDWT;               // cargo DWT
        double pd  = 2*((cDWT/hr) + 0.5);            // port days
        double RTPA= 350/(sd + pd);                  // round trips per year
        double vc  = (fc + pc) * RTPA;               // voyage costs (£/t)
        double ac  = cc + rc + vc;                   // annual costs(£/t)
        double acrg= cDWT * RTPA;                    // annual cargo (t/yr) **** Maximize
        double trc = ac/acrg;                        // transportation cost **** Minimize

        double KB  = 0.53*T;                         // vertical center of buoyancy
        double BMT = ((0.085*CB - 0.002)*pow(B,2)) /(T*CB );   // metacentric radius
        double KG  = 1.0 + 0.52*D;                   // vertical center of gravity
        double GMT = KB + BMT - KG;


        // criteria values

        crits[0]  = trc;          // transportation cost (£/t)  **** Minimize
        crits[1]  = lsw;          // light ship weight         **** Minimize
        crits[2]  = acrg;         // annual cargo (t/yr)       **** Maximize

        // functions values

        funcs[0]  = L/B;                          // L/B >= 6
        funcs[1]  = L/D;                          // L/D <= 15
        funcs[2]  = L/T;                          // L/T <= 19
        funcs[3]  = T - 0.45*pow(DWT,0.31);       // T - 0.45*DWT^0.31 <= 0
        funcs[4]  = T - 0.7*D - 0.7;              // T - 0.7*D - 0.7 <= 0
        funcs[5]  = DWT;                          // 25,000 <= DWT <= 500,000
        funcs[6]  = Fn;                           // Fn <= 0.32
        funcs[7]  = GMT -0.07*B;                  // GMT -0.07*B >= 0


        return (funcs[0]);
}

SHIP_API double WINAPI f2(double Alpha[])
{
        return (funcs[1]);
}

SHIP_API double WINAPI f3(double Alpha[])
{
        return (funcs[2]);
}

SHIP_API double WINAPI f4(double Alpha[])
{
        return (funcs[3]);
}

SHIP_API double WINAPI f5(double Alpha[])
{
        return (funcs[4]);
}

SHIP_API double WINAPI f6(double Alpha[])
```

```
{
        return (funcs[5]);
}

SHIP_API double WINAPI f7(double Alpha[])
{
        return (funcs[6]);
}

SHIP_API double WINAPI f8(double Alpha[])
{
        return (funcs[7]);
}


/*************************************************************************************
Criteria functions
*************************************************************************************/

SHIP_API double WINAPI c1(double Alpha[])
{
        return (crits[0]);
}

SHIP_API double WINAPI c2(double Alpha[])
{
        return (crits[1]);
}

SHIP_API double WINAPI c3(double Alpha[])
{
        return (crits[2]);
}

/REFERENCES:
[1] OscTask (CPP file) (STATNIKOV R.B.)
[2] STATNIKOV R.B. 2003, MOVI 1.3 Software Package User's Manual./
```

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APPENDIX E. MICROSOFT EXCEL TEST OF BULK CARRIER DESIGN OPTIMIZATION MODEL RESULTS

Number of vector : 6092

Values of vectors:		Values of functional relations:	MOVI	EXCEL TEST	ERROR
1 - L = p1	166.96355	1 - L/B >= 6	6.13717863	6.13717863	0
2 - B = p2	27.205261	2 - L/D <= 15	12.18814111	12.18814111	-6.03961E-14
3 - D = p3	13.698853	3 - L/T <= 19	16.33614986	16.33614986	-1.3145E-13
4 - T = p4	10.220496	4 - T - 0.45*DWT^0.31 <= 0	-0.67016587	10.22049561	10.89066148
5 - CB = p5	0.7479639	5 - T - 0.7*D - 0.7 <= 0	-0.068701172	10.22049561	10.28919678
6 - Vk = p6	14.893066	6 - 25,000 <= DWT <= 500,000	29107.54843	29107.54843	4.00178E-11
		7 - 25,000 <= DWT <= 500,000	29107.54843	29107.54843	4.00178E-11
		8 - Fn <= 0.32	0.189329042	0.189329042	4.996E-16
		9 - GMT -0.07*B >= 0	1.350806609	3.255174895	1.904368286
		Values of criteria:	**MOVI**	**TEST**	**ERROR**
		1 - transportation cost (minimize)	9.556142321	9.556142321	-2.30926E-14
		2 - light ship weight (minimize)	6484.337809	6484.337809	-4.00178E-11
		3 - annual cargo (maximize)	447577.4248	447577.4248	5.23869E-10

Independent variables (6):	
length (m) L	**166.96**
beam (m) B	**27.21**
depth (m) D	**13.70**
draft (m) T	**10.22**
block coefficient C_B	**0.75**
speed (knots) V_k	**14.89**
displacement $= 1.025\ L\ B\ T\ C_B$ (t)	35,591.886
$V = 0.5144\ V_k$ m/s;	7.661
$g = 9.8065$ m/s^2	9.8065
F_n =Froude number $= V/(g\,L)^{0.5}$	0.189
$\mathbf{a} = 4{,}977.06\ C_B^{\,2} - 8{,}105.61\ C_B + 4{,}456.51$	**1,178.223**
$\mathbf{b} = -\ 10{,}847.2\ C_B^{\,2} + 12{,}817\ C_B - 6{,}960.32$	**-3,442.133**
AC $= \mathbf{a} + \mathbf{b}\ F_n$	526.527
P = power = **displacement**$^{2/3}\ V_k^{\,3}/(\mathbf{a} + \mathbf{b}\ F_n)$	**6,788**
W_s = steel weight $= 0.034\ L^{1.7}\ B^{0.7}\ D^{0.4}\ C_B^{\,0.5}$	5,079.334
W_o = outfit weight $= 1.0\ L^{0.8}\ B^{0.6}\ D^{0.3}\ C_B^{\,0.1}$	927.433
W_m = machinery weight $= 0.17\ P^{0.9}$	477.571
ship cost $= 1.3\ (2{,}000\ W_s^{\,0.85} + 3{,}500\ W_o + 2{,}400\ P^{0.8})$ (£/t)	11,519,037.500
capital costs = 0.2 **ship cost** (£/t)	2,303,807.500
light ship weight $= W_s + W_o + W_m$ (t)	**6,484.3**
DWT = deadweight = **displacement** – light ship	**29,108**

running costs = 40,000 **DWT**$^{0.3}$	873,497.527
daily consumption = 0.19 P · 24/1,000 + 0.2	31.155
round trip miles = 5,000 (nm)	5,000.000
sea days = **round trip miles**/24V_k	13.989
fuel price = 100 (£/t)	100.000
fuel cost = 1.05 **daily consumption** · **sea days** · **fuel price** (£/t)	45,760.584
port cost = 6.3 **DWT**$^{0.8}$ (£/t)	23,471.727
fuel carried = **daily consumption** · (**sea days** + 5)	591.590
miscellaneous DWT = 2.0 DWT$^{0.5}$	341.219
cargo DWT = **DWT** – **fuel carried** – **miscellaneous DWT**	28,174.740
handling rate = 8,000 (t/day)	8,000.000
port days = 2[(**cargo DWT**/**handling rate**) + 0.5]	8.044
RTPA = round trips per year = 350/(**sea days** + **port days**)	15.886
voyage costs = (**fuel cost** + **port cost**) · **RTPA**	1,099,808.544
annual costs = **capital costs** + **running costs** + **voyage costs** (£/t)	4,277,113.571
annual cargo = **cargo DWT**· **RTPA** (t/yr)	**447,577**
transportation cost (£/t) = **annual costs**/**annual cargo**	**9.556**
vertical center of buoyancy = $KB = 0.53\ T$	5.417
metacentric radius = $BM_T = (0.085\ C_B - 0.002)B^2/(T\ C_B)$	5.962
vertical center of gravity = $KG = 1.0 + 0.52\ D$	8.123
$GM_T = KB + BM_T - KG$	3.255
Constraints (13):	
$L/B \geq 6$	6.137
$L/D \leq 15$	12.188
$L/T \leq 19$	16.336
$T \leq 0.45$ DWT$^{0.31}$	10.220
$T \leq 0.7\ D + 0.7$	10.220
3,000 ≤ DWT ≤ 500,000	29,107.548
	29,107.548
$0.63 \leq C_B \leq 0.75$	0.748
	0.748
$14 \leq V_k \leq 18$	14.893
	14.893
$F_n \leq 0.32$	0.189
$GM_T = KB + BM_T - KG \geq 0.07\ B$	3.255
Case 1: added 14th constraint	
L ≤ 274.32 m (900 ft), perhaps due to dock, lock, or turning basin limits	166.964
minimum DWT raised from 3,000 t to 25,000 t	29,107.548

APPENDIX F. MATLAB CODE OF MIT FUNCTIONAL SHIP DESIGN SYNTHESIS MODEL

Ship.m

```
function [c1,c2,c3,c4,c5,c6,f1,f2,f3,f4,f5,f6,f7,f8,f9,f10,f11] ship(p1, ↙
p2,p3,p4,p5,p6,p7,p8,p9,p10,p11,p12,p13,p14,p15,p16,p17,p18,p19,p20,p21, ↙
p22,p23,p24,p25,p26,p27,p28,p29,p30,p31,p32,p33,p34,p35,p36,p37,p38,p39, ↙
p40,p41,p42,p43,p44,p45)
%
% MIT FUNCTIONAL SHIP DESIGN SYNTHESIS MODEL (Surface Combatants)
% This model is the MATLAB version of the
% MIT FUNCTIONAL SHIP DESIGN SYNTHESIS MODEL (in Mathcad)
% for Surface Combatants, which was a modified version of the
% Axiomatic Design Model created by John Szatkowski in 2000.
%
% Kivanc Ali ANIL, 2004
%------------------------------------------------------------
% hp     = 33000 ft.lbf/min
% knt    = 1.69 ft/sec
% mile   = knt.hr
% lton   = 2240 lb
% 1 hp   = 0.74568247 kW
%------------------------------------------------------------
% CONSTANTS *************************************************
%------------------------------------------------------------
TSW      = 59;                       % Seawater Temp
NuSW     = 1.2817*10^-5;             % Seawater Viscosity (ft^2/sec)
RhoSW    = 1.9905 ;                  % Seawater Density (slug/ft^3)
AlphaSW  = 35;                       % Seawater Specific Volume (ft^3/lton)
AlphaW   = 36;                       % Fresh Water Specific Volume (ft^3/lton)
RhoA     = .0023817 ;                % Air Density (slug/ft^3)
CAA      = .7;                       % Air Drag Coefficient
AlphaLO  = 39;                       % Lube Oil Specific Volume (ft^3/lton)
AlphaHF  = 43;                       % Helo Fuel Specific Volume (ft^3/lton)
AlphaF   = 43;                       % Endurance Fuel Specific Volume (ft^3/lton)
g        = 32.174 ;                  % (ft/sec^2)
%------------------------------------------------------------
r1      = 30;
r2      = 20;
r3      = 4000;
r4      = 45;
r5      = .1;
r6      = .5;
r7      = 5;
r8      = 53;
%------------------------------------------------------------
%p1      = 356.25;
%p2      = 39.375;
%p3      = 2;            % DISCRETE
%p4      = 0.62125;
%p5      = 0.803125;
%p6      = 8.5;
%p7      = 5;
%p8      = 8.05;
%p9      = 2;            % DISCRETE
%p10     = .97;
%p11     = 2;            % DISCRETE
%p12     = 1;            % DISCRETE
%p13     = 17.6;
%p14     = 1;            % DISCRETE
%p15     = 12;
%p16     = 100.5;
%p17     = 538.9;
%p18     = 43.8;
%p19     = 0;            % DISCRETE
%p20     = .28;
%p21     = 27;           % DISCRETE
%p22     = 14.2;
%p23     = -3.00;
%p24     = 325;
%p25     = 3.5;          % DISCRETE
%p26     = 2;            % DISCRETE
%p27     = 1;            % DISCRETE
```

```
%p28      = 46.1;
%p29      = 14.7;
%p30      = 2;
%p31      = 1700;
%p32      = 60.5;
%p33      = 2;            % DISCRETE
%p34      = 2;            % DISCRETE
%p35      = 370;
%p36      = 1;
%p37      = .079;
%p38      = 379.2;
%p39      = 1;            % DISCRETE
%p40      = 1;            % DISCRETE
%p41      = -10;
%p42      = 1.1;
%p43      = .67;
%p44      =  5;           % DISCRETE
%p45      =  4;           % DISCRETE
%-------------------------------------------------------------
% ASSIGN VARIABLES ***************************************
%-------------------------------------------------------------
% DESIGN REQUIREMENTS
VS        = r1 ;                   % Sustained Speed (knt)
Ve        = r2 ;                   % Endurance Speed (knt)
E         = r3 ;                   % Range (mile)
TS        = r4 ;                   % Stores period (day)
WM        = r5 ;                   % Weight Margin (fraction of lightship weight)
KGMARG    = r6 ;                   % KG Margin (ft)
NO        = r7 ;                   % Manning: Number of Officers
NE        = r8 ;                   % Manning: Number of Enlisted
NT        = NO + NE ;              % Manning: Total
%-------------------------------------------------------------
% BASIC DESIGN PARAMETERS
LWL       = p1 ;                   % Length (ft)
B         = p2 ;                   % Beam (ft)
Ndecks    = p3 ;                   % # Hull Decks
                                   % DISCRETE
CP        = p4 ;                   % Prismatic Coefficient:
                                   % Typical range: .54 - .64, Reference:
                                   % "Hydrodynamics in Ship Design"
                                   % by Saunders, SNAME 1957 Vol II (pg 466)
CX        = p5  ;                  % Maximum Section Coefficient
                                   % Typical range: .7 - .85, Reference:
                                   % "Hydrodynamics in Ship Design"
                                   % by Saunders, SNAME 1957 Vol II (pg 469)
HDKh      = p6 ;                   % Avg Hull Deck Height (ft)
BILGE     = p7 ;                   % Bilge Height (ft)
HDKd      = p8 ;                   % Avg. Deckhouse Deck Heigh (ft)
%-------------------------------------------------------------
% PROPULSION SYSTEM
NPENG     = p9;                    % # Propulsion Engines
                                   % DISCRETE
eta       = p10 ;                  % Mechanical Efficiency
NDIE      = p11 ;                  % Deckhouse decks impacted by propulsion
                                   % and generator inlet/exhaust
                                   % DISCRETE
NHPIE     = p12 ;                  % Hull decks impacted by propulsion inlet/exhaust
                                   % DISCRETE
WF46      = p13 ;                  % LO weight (lton)
NP        = p14 ;                  % Number of propellers
                                   % DISCRETE
DP        = p15 ;                  % Selected propeller diameter (ft)
LS        = p16 ;                  % Selected shaft length (ft)
%-------------------------------------------------------------
% SHIP CONTROL SYSTEM
ADB       = p17 ;                  % Bridge area (ft^2)
WIC       = p18 ;                  % Gyro/IC/Navigation Weight (W420,W430) (lton)
Nfins     = p19 ;                  % Number of Fin Stabilizer Pairs
                                   % DISCRETE
%-------------------------------------------------------------
% COMBAT SYSTEMS
CSD       = p20 ;                  % Drag Coefficient
ASD       = p21 ;                  % Sonar Area (ft^2)
                                   % (SQS-56: 27 ft^2 ; SQS-53C: 215 ft^2)
                                   % DISCRETE (27,215)
W498      = p22 ;                  % Sonar Dome Water Weight (lton)
VCG498    = p23 ;                  % Sonar Dome Water Vertical Center of Gravity (ft)
%-------------------------------------------------------------
% DECKHOUSE
% Area Requirements:
```

```
ACOXO    = p24;                % Living Area for CO and XO (ft^2)
vf       = p25 ;               % Choose volume factor:
                               % for FFG 7  type deckhouse: vf = 3.5
                               % for DDG 51 type deckhouse: vf = 5.2
                               % DISCRETE (3.5,5.2)
CDHMAT   = p26 ;               % Choose deckhouse material
                               % Aluminum - CDHMAT = 1
                               % Steel    - CDHMAT = 2
                               % DISCRETE (1,2)
%------------------------------------------------------------
% AUXILIARY SYSTEMS
CPS      = p27 ;               % Collective Protection System(Ventilation),CPS=1,
                               % zero if no CPS
                               % DISCRETE (0,1)
kWM      = p28 ;               % Miscellaneous (kW)
W593     = p29 ;               % Environmental Support Systems Weight (lton)
W171     = p30 ;               % Mast Weight (lton)
VWASTE   = p31 ;               % Waste Oil Volume (ft^3)
W598     = p32 ;               % Aux Systems Operating Fluid Weight (lton)
%------------------------------------------------------------
% SHIP SERVICE GENERATORS
NG       = p33 ;               % Number of generators
                               % DISCRETE
NHeIE    = p34 ;               % Hull decks impacted by generator inlet/exhaust
                               % DISCRETE
%------------------------------------------------------------
% FUEL
WBP      = p35 ;               % Burnable propulsion endurance fuel weight (lton)
                               % Iterate WBP to meet range requirement
%------------------------------------------------------------
% HULL GEOMETRY
D10C     = p36 ;               % Constant for Depth at Station 10, D10xC
                               % Depth at Station 10(D10x) must be > or = D10MIN
                               % and D10x = D10xC* D10MIN. Therefore
                               % select D10xC > or = 1
FP       = p37 ;               % Payload Weight Fraction;
WOFH     = p38 ;               % Hull Fittings (lton)
CHMAT    = p39 ;               % Hull Material
                               % (OS: CHMAT=1.0; HTS: CHMAT=0.93)
                               % DISCRETE (0.93,1)
CBVC     = p40;                % Clean Ballast Volume Constant
                               % CBVC = 0  for compensated
                               % CBVC = 1  for uncompensated system
                               % DISCRETE (0,1)
%------------------------------------------------------------
% RESISTANCE
LCB      = p41 ;               % enter the LCB from midships
                               % as percent of length, (-) = aft
%------------------------------------------------------------
% PROPULSIVE POWER BALANCE
PMF      = p42;                % Power Margin Factor
                               % (margin for concept design = 10%)
PC       = p43 ;               % Approximate Propulsive Coefficient (PC)
%------------------------------------------------------------
% Choose propulsion engines:
SELECTP  = p44 ;               % DISCRETE (1,2,3,4,5,6,7)
% Choose Generators:
SELECTG  = p45 ;               % DISCRETE (1,2,3,4,5,6,7)
%------------------------------------------------------------
% Propulsion engines:
% (data from the ASSET library in the Machinery Wizard)
%
if SELECTP == 1 % Diesel, PC 4.2V10
          % Weight   Length  Width   Height  Power   SFC         Inlet   Exhaust
          %                                                      X-sect  X-sect
          % (lton)   (ft)    (ft)    (ft)    (hp)    (lbm/hp-hr) (ft^2)  (ft^2)
          % ------   ------  ------  ------  ------  ----------  ------  ------
SPRSHTpr = [189.3    34.2    17      24.5    16270   0.313       34.5    15.1 ];
elseif SELECTP == 2 % Diesel, F/PC2/16-DD
SPRSHTpr = [79.6     28      12.15   12.76   10400   0.34        21.7    9.7  ];
elseif SELECTP == 3 % Diesel, PC 4.2V14
SPRSHTpr = [257.14   38.3    17.25   22.2    22778   0.31        46.2    22.3 ];
elseif SELECTP == 4 % Diesel, PC 4.2V18
SPRSHTpr = [312.5    44.8    17.25   22.2    29286   0.31        59.4    28.7 ];
elseif SELECTP == 5 % Gas Turbine, GE LM2500-30
SPRSHTpr = [3.1      15.65   5.2     5.2     26250   0.393       99.6    51   ];
elseif SELECTP == 6 % Gas Turbine, Other (DDG 51)
SPRSHTpr = [3.1      15.65   5.2     5.2     25775   0.41        106     53.1 ];
elseif SELECTP == 7 % Gas Turbine, GE LM5000
SPRSHTpr = [4.8      19.67   6.5     6.5     39100   0.3868      159.3   79   ];
```

```
end
% Generators:
% (data from the ASSET library in the Machinery Wizard)
if SELECTG == 1 % CAT 3608 IL8
          % Weight   Length  Width   Height  Power   SFC          Inlet   Exhaust
          %                                                        X-sect  X-sect
          % (lton)   (ft)    (ft)    (ft)    (hp)    (lbm/hp-hr)  (ft^2)  (ft^2)
          % ------   ------  ------  ------  ------  ---------    ------  ------
SPRSHTge = [18.7     15.8    5.74    8.62    3390    0.31         0       2.4  ];
elseif SELECTG == 2 % GM 16-645E5
SPRSHTge = [16.8     17.64   5.64    9.25    3070    0.38         0       2.2  ];
elseif SELECTG == 3 % Other (LSD 41)
SPRSHTge = [11.4     15.18   6.46    9.79    2100    0.37         0       2.1  ];
elseif SELECTG == 4 % F 38TD8-1/8-12
SPRSHTge = [21.8     30.1    7       7       3500    0.33         0       3    ];
elseif SELECTG == 5 % DDA 501-K34
SPRSHTge = [0.6      7.5     2.8     2.6     4600    0.473        24      11.7 ];
elseif SELECTG == 6 % DDA 570-KA
SPRSHTge = [0.6      6       2.63    2.58    5965    0.4763       23.9    11.6 ];
elseif SELECTG == 7 % GE LM 500
SPRSHTge = [0.57     7.2     2.8     2.8     4500    0.4812       20.9    10.2 ];
end
%------------------------------------------------------------
% PERFORM COMPUTATIONS ************************************
%------------------------------------------------------------
% BASIC DESIGN PARAMETERS
CLB       = LWL/B ;                  % (Typical range: 7.5 - 10)
                                     % CONSTRAINT !!!
CW        = .236 + .836*CP;          % Reference:"Hydrodynamics in Ship Design"
                                     % by Saunders, SNAME 1957 Vol II (pg 466)
HDK       = (HDKh + HDKd)/2;         % Avg. Overall Deck Height (ft)
%------------------------------------------------------------
% PROPULSION SYSTEM
WPE       = SPRSHTpr(1)*2240;        % Weight (lb)
PBPENG    = SPRSHTpr(5) ;            % Brake Power (hp)
FR        = SPRSHTpr(6) ;            % Fuel Rate (lb/(hp.hr))
AIE       = SPRSHTpr(7)+SPRSHTpr(8) ;% Inlet/Exhaust X-sect (ft^2)
% Module size:
Lmod      = SPRSHTpr(2) ;            % (ft)
Bmod      = SPRSHTpr(3) ;            % (ft)
Hmod      = SPRSHTpr(4) ;            % (ft)
% Power:
PIBRAKE   = NPENG * PBPENG ;         % Total Brake Horsepower
PI        = eta * PIBRAKE ;          % Total Shaft Horsepower
% Area:
APIE      = NPENG * AIE ;            % Inlet/exhaust Xsect area for PE  (ft^2)
ADIEP     = 1.4 * NDIE * APIE;       % Engine Inlet/Exhaust (Deckhouse) (ft^2)
AHIEP     = 1.4 * NHPIE * APIE;      % Engine Inlet/Exhaust (Hull) (ft^2)
% Lube Oil:
VLO       = 1.02*1.05*WF46*AlphaLO;  % (ft^3) Allow for tank structure and expansion
                                     % (2% for structure, 5% for expansion)
% Propellers:
WPR       = 1.15*.05575*NP*DP^(5.497- .0433*DP)/2240 ;
                                     % Propeller Weight:(W245) (lton)
% Shafting:
NS        = NP ;                     % Number of shafts
WS        = 1.15*.356*NS*LS ;        % Shafting Weight:(W243)(lton)
WST       = WS + WPR ;               % Total Shafting and Propellers (lton)
% Required Power for Propulsion System (kW):
kWP       = .00466*PIBRAKE ;         % Most of the electrical power requirements
                                     % in this model come from the
                                     % ASSET Machinery Module User's Manual.
                                     % The equations are curve fits of
                                     % data for DD 963, FFG 7, CG 47 and DDG 51 at
                                     % the winter cruise condition.
% Machinery Box Size:
BMB       = 1.5 * Bmod * NPENG ;     % Dimensions (ft)
LMB       = 1.5 * Lmod * NS ;        % Dimensions (ft)
HMB       = 2.5 * Hmod ;             % Dimensions (ft)
AMB       = LMB * BMB ;              % Area (ft^2)
VMB       = HMB * AMB ;              % Volume (ft^3)
% Basic Machinery Weight:(W230+W241/W242+W250-W290)
WBM       = PI*(9 + 12.4*(PI*10^-5-1)^2)/2240 ;
%------------------------------------------------------------
% SHIP CONTROL SYSTEM
% Steering System Electrical Power Required:
W237      = 0 ;                      % Aux Propulsion (APU) Weight (lton)
VCG237     = 0    ;                      % Aux Propulsion (APU) Vertical Center of Gravity
(ft)
```

```
Test      = B/3 ;                    % (ft) To calculate electrical power required
                                     % for steering, need to estimate draft.
                                     % Use approximate Beam-to-Draft ratio for
                                     % a surface combatant of 3.
kWS       = 5.83 * LWL * Test/1000;  % Power Required (kW) (eqn from ASSET)
kWfins    = Nfins*50 ;               % (kW) Fin Stabilizers (for one pair,
                                     % electric power requirement = 50 kW)
W2        = WBM + WST + W237 ;       % Total Propulsion Weight (lton)
%-----------------------------------------------------------
% PAYLOAD
WP        = 243.746002197265;        % Total Payload Weight (lton)

WFL       = WP/FP;                   % Full Load Weight (lton)
DELTAFL   = WFL ;                    % Full Load Displacement (equal to full load weight)
VFL       = DELTAFL*AlphaSW ;        % Volume at LWL (ft^3)
Te        = VFL/(CP*CX*LWL*B) ;      % Draft
D0e       = 1.011827*Te-6.36215*10^-6*LWL^2+2.780649*10^-2*LWL+Te ;
                                     % Depth of Station  0 (ft)
D10e      = D10C*(max([HMB Ndecks*HDK + BILGE LWL/15]))  ;
                                     % Depth of Station 10 (ft)
D20e      = .014*LWL*(2.125+1.25*10^-3*LWL)+Te ;
                                     % Depth of Station 20 (ft)
% INPUT: [D0e D10e D20e]
D3         = D0e-(D0e-D10e)*0.3;
D6p5       = D0e-(D0e-D10e)*0.65;
D15        = D10e-(D10e-D20e)*0.5;
BL         = 0;
%
% After changing the systems  equations may need to be adjusted!
% ---------------------------------------------------------------------------
%   1          2       3      4               5               6       7       8
%   WT         VCG     VCG    HULL            DKHS            CRUISE BATTLE  WT
%              DATUM   FT AD  FT^2            FT^2            KW      KW      MOMENT
%   ----       -----   -----  -----           -----           ------  ------  ------
s =[1.000      D10e   16.100  0.000000        62.829056       6.000   8.000   0       ;...
    2.370      D10e   29.270  0.000000        0.000000        3.200   4.000   0       ;...
    16.450     D10e   38.989  0.000000        939.853824      67.250  118.500 0       ;...
    0.000      0.000  0.000   0.000000        0.000000        0.000   0.000   0       ;...
    7.160      BL     9.300   245.614272      0.000000        15.000  25.000  0       ;...
    3.050      0.000  0.000   0.000000        0.000000        0.000   0.000   0       ;...
    1.000      0.000  0.000   0.000000        0.000000        0.000   0.000   0       ;...
    3.616      D10e   16.100  0.000000        534.154560      15.000  73.000  0       ;...
    0.000      0.000  0.000   0.000000        0.000000        0.000   0.000   0       ;...
    7.350      D3     -6.200  93.598080       0.000000        25.000  35.000  0       ;...
    0.010      0.000  0.000   93.598080       0.000000        0.000   0.000   0       ;...
    7.550      0.000  0.000   502.524864      0.000000        0.000   0.000   0       ;...
    7.970      D6p5   -11.800 617.101824      0.000000        0.000   0.000   0       ;...
    2.700      D15    3.000   0.000000        360.000000      0.600   1.100   0       ;...
    10.230     D15    3.000   0.000000        458.415424      0.000   0.000   0       ;...
    8.860      D6p5   -9.200  0.000000        0.000000        0.000   0.000   0       ;...
    6.470      D3     -28.400 0.000000        0.000000        0.000   0.000   0       ;...
    1.200      D15    3.000   0.000000        0.000000        0.000   0.000   0       ;...
    5.370      D15    3.000   0.000000        0.000000        0.000   0.000   0       ;...
    1.000      D6p5   -3.600  1036.464256     0.000000        60.000  60.000  0       ;...
    1.000      D10e   -7.970  210.864640      187.518912      80.000  80.000  0       ;...
    0.240      D10e   0.000   200.000000      0.000000        3.000   0.000   0       ;...
    0.380      D10e   0.000   0.000000        238.000000      3.000   0.000   0       ;...
    4.860      D15    -11.000 30.000000       0.000000        2.000   0.000   0       ;...
    31.100     D15    -1.600  219.000000      33.000000       4.400   0.000   0       ;...
    1.040      D15    -4.500  194.000000      75.000000       0.000   0.000   0       ;...
    9.870      D15    4.800   0.000000        588.000000      0.000   0.000   0       ;...
    12.730     D15    4.500   0.000000        3406.000000     5.600   0.000   0       ;...
    9.420      D15    5.000   357.000000      0.000000        0.000   0.000   0       ;...
    63.800     BL     10.400  0.000000        0.000000        0.000   0.000   0       ;...
    1.070      D10e   21.500  40.000000       130.000000      6.500   6.500   0       ;...
    3.500      D20e   -2.000  283.591424      0.000000        3.000   4.200   0       ;...
    1.070      D10e   13.600  0.000000        0.000000        2.400   2.400   0       ;...
    1.700      D10e   13.600  0.000000        169.337216      0.000   0.000   0       ;...
    2.200      D10e   13.600  0.000000        0.000000        0.000   0.000   0       ;...
    0.450      D10e   -16.100 0.000000        0.000000        8.000   8.000   0       ;...
    0.000      D6p5   -19.850 35.072384       0.000000        0.000   0.000   0       ;...
    0.000      D6p5   -10.000 0.000000        0.000000        0.000   0.000   0       ;...
    0.000      D3     -8.000  0.000000        0.000000        0.000   0.000   0       ;...
    1.700      D10e   13.600  0.000000        74.663296       0.000   0.000   0       ;...
    4.260      D10e   -6.000  0.000000        0.000000        0.000   0.000   0       ];
%
% 8
% WT
% MOMENT
% ------
```

```
[row column] = size(s);
for i = 1: row
    s(i,8)=s(i,1)*(s(i,2)+s(i,3));
end
%
% SYSTEM DESCRIPTION                              WT KEY         AREA KEY
% -------------------                             ------         --------
% NAVIGATION EQUIPMENT:
% s(1,:) : NAVIGATION SYSTEM                      W420           A1322
% SENSORS:
% s(2,:) : IFF                                    W455           A1121
% s(3,:) : MULTIPLE MODE/FUNCTION RADAR           W456           A1121
% s(4,:) : TOWED TORPEDO ALERTMENT ARRAY          W462           A1122
% s(5,:) : BOW SONAR                              W463           A1122
% s(6,:) : ELECTRONIC WARFARE SENSORS             W466           A1120
% s(7,:) : ELECTRO OPTIC SENSOR                   W466           A1120
%
% WEAPONS SYSTEMS:
% s(8,:) : MISSILE WEAPON CONTROL SYSTEM          W482           A1220
% s(9,:) : INTEGRATED FIRE CONTROL SYSTEMS        W484           A1200
% s(10,:): GUN                                    W711           A1210
% s(11,:): AMMUNITION HANDLING                    W712           A1210
% s(12,:): AMMUNTION STOWAGE -
%              READY SERVICE AND MAGAZINES        W713           A1210
% s(13,:): LAUNCHING SYSTEMS, MISSILE
%              MK 48 Mod 2 - 8 Cells)             W721           A1220
% s(14,:): TORPEDO TUBES ON DECK                  W750           NONE
% s(15,:): SURFACE TO SURFACE MISSILE
%              LAUNCHER ( Mk 140 LtWt - 2 Quad
%              Launchers)                         W721           A1220
% s(16,:): MISSILES - 32 ESSM                     WF21           A1220
% s(17,:): AMMO - 300 Rounds                      WF21           A1210
% s(18,:): LIGHTWEIGHT ASW TORPEDOES - 6          WF21           NONE
% s(19,:): SURFACE TO SURFACE MISSILES - 8        WF21           NONE
%
% NETWORK SYSTEMS:
% s(20,:): CIC ELEX                               W411           A1131
% s(21,:): EXCOMM + MINI CEC                      W440           A1111
%
% EMBARKED AIRCRAFT - AUTONOMOUS/REMOTE OPERATED VECHICLES:
% s(22,:): Minehunting AUV/Remote
%              Minehunting System                 W478           A1142
% s(23,:): UAV, Operating System                  W495           A1142
% s(24,:): LAMPS Mk III Fuel System               W542           A1380
% s(25,:): LAMPS Mk III RAST
%              System/Helo Control                W588           A1312
% s(26,:): LAMPS Mk III Aviation Shop,
%              Office                             W665           A1360
% s(27,:): LAMPS Mk III Torpedos
%              (Mk 46 x 18), Sonobuoys
%              and Pyrotechnics                   WF22           A1374
% s(28,:): LAMPS Mk III SH60
%              Helicopter and Hangar              WF23           A1340
% s(29,:): LAMPS Mk III Aviation
%              Support and Spares                 WF26           A1390
% s(30,:): LAMPS Mk III Fuel                      WF42           A1380
%
% COUNTERMEASURES:
% s(31,:): PASSIVE ECM                            W472           A1141
% s(32,:): TORPEDO DECOY                          W473           A1142
% s(33,:): TORPEDO COUNTERMEASURES                W474           NONE
% s(34,:): COUNTERMEASURES/DECOY STOWAGE          W763           NONE
% s(35,:): COUNTERMEASURES/DECOY
%              CANNISTERS - 100 RDS               WF21           NONE
%
% PAYLOAD SUPPORT/AUX SYSTEMS:
% s(36,:): RADAR - COOLING SYSTEM                 W532           NONE
% s(37,:): VLS AUXILIARY EQUIPMENT                W555           NONE
%
% PAYLOAD OUTFIT ITEMS:
% s(38,:): VLS ARMOR - LEVEL III HY-80            W164           NONE
% s(39,:): GUN HY-80 ARMOR LEVEL II               W164           NONE
%
% MISC SYSTEMS:
% s(40,:): 20mm STOWAGE                           W763           NONE
% s(41,:): 20mm AMMUNITION - 8000 rounds          WF21           NONE
% ---------------------------------------------------------------------------
%GROUP WF20 (expendable ordnance - WT KEY WF20)
WTWF20   = s(16,1)+s(17,1)+s(18,1)+s(19,1)+s(27,1)+s(28,1)+s(29,1)+s(35,1)+s(41,1);
hullWF20 = s(16,4)+s(17,4)+s(18,4)+s(19,4)+s(27,4)+s(28,4)+s(29,4)+s(35,4)+s(41,4);
```

```
DKHSWF20 = s(16,5)+s(17,5)+s(18,5)+s(19,5)+s(27,5)+s(28,5)+s(29,5)+s(35,5)+s(41,5);
WTMWF20  = s(16,8)+s(17,8)+s(18,8)+s(19,8)+s(27,8)+s(28,8)+s(29,8)+s(35,8)+s(41,8);
% VARIABLE MILITARY PAYLOAD
% (expendable ordnance + helo fuel, WT KEY WF20+WF42)
WTVARIAB = WTWF20  + s(30,1);
WTMVARIA = WTMWF20 + s(30,8);
% ARMAMENT (WT KEY W500,W600,W700,WF20)
hullARMA = s(10,4)+s(11,4)+s(12,4)+s(13,4)+s(14,4)+s(15,4)+s(22,4)+s(23,4)+...
           s(24,4)+s(25,4)+s(26,4)+s(34,4)+s(36,4)+s(37,4)+s(40,4)+hullWF20;
DKHSARMA = s(10,5)+s(11,5)+s(12,5)+s(13,5)+s(14,5)+s(15,5)+s(22,5)+s(23,5)+...
           s(24,5)+s(25,5)+s(26,5)+s(34,5)+s(36,5)+s(37,5)+s(40,5)+DKHSWF20;
% TOTAL PAYLOAD
totalWT  = sum(s(:,1));
totalhull= sum(s(:,4));
totalDKHS= sum(s(:,5));
totalKW  = sum(s(:,6));
totalWTM = sum(s(:,8));
Wx       = [];
Wx(1)    = WTWF20 ;                 % WF20
Wx(2)    = s(28,1);                 % WF23
Wx(3)    = s(30,1);                 % WF42
Wx(4)    = 0;
Wx(5)    = s(38,1)+s(39,1);         % W164
Wx(6)    = 0;                       % W165
Wx(7)    = s(1,1)+s(2,1) +s(3,1) +s(4,1) +s(5,1) +s(6,1) +s(7,1) +s(8,1)+...
           s(9,1)+s(20,1)+s(21,1)+s(22,1)+s(23,1)+s(31,1)+s(32,1)+s(33,1);
                                    % WP400
Wx(8)    = s(24,1)+s(25,1)+s(36,1)+s(37,1) ;
                                    % WP500
Wx(9)    = s(26,1) ;                % WP600
Wx(10)   = s(10,1)+s(11,1)+s(12,1)+s(13,1)+s(14,1)+s(15,1)+s(34,1)+s(40,1);
CUM      =  [];
CUM(1)   =     totalWT  ;           % WP
CUM(2)   =     WTVARIAB  ;          % WVP
CUM(3)   =     totalWTM /totalWT  ; % VCG P:
CUM(4)   =     WTMVARIA /WTVARIAB;  % VCG VP:
CUM(5)   =     totalKW;             % KWP
Ax       = [];
Ax(1)    = totalhull-hullARMA ;     % A HPC
Ax(2)    = totalDKHS-DKHSARMA ;     % A DPC
Ax(3)    = hullARMA  ;              % A HPA
Ax(4)    = DKHSARMA  ;              % A DPA
%-----------------------------------------------------------
% COMBAT SYSTEMS
% Sonar Dome:
% Aircraft Fuel:
WF42     = Wx(3) ;                  % Weight (from Payload Spreadsheet) (lton)
VHF      = 1.02*1.05*WF42*AlphaHF;  % Volume (allow 2% for structure, 5% for expansion)
% Payload Deck Area/Weight:
ADPA     = Ax(4) ;                  % Deckhouse Armament (W500, W600,
                                    % W700, WF20) Area (ft^2)
W7       = Wx(10) ;                 % Armament Weight (all W700) (lton)
WP400    = Wx(7) ;                  % Command and Surveillance Payload
                                    % (W400 less 420 and 430)(lton)
                                    % Payload Deck Areas:
AHPC     = Ax(1) ;                  % Hull (ft^2) C&D  (W400)
ADPC     = Ax(2) ;                  % Deckhouse (ft^2) C&D  (W400)
ADPR     = 1.15*ADPA + 1.23*ADPC ;  % Deckhouse payload area (ft^2)(including access)
WF20     = Wx(1) ;                  % Ordnance Weight (lton) (incl helo wt, WF23)
WVP      = CUM(2) ;                 % Variable Payload  (lton)
WCC      = .04*(WP400 + WIC) ;      % Command and Control Cabling Weight  (lton)
W4       = WP400 + WIC + WCC+ W498; % Group 400 Weight  (lton)
%-----------------------------------------------------------
% DECKHOUSE
% Area Requirements:
ADO      = 75*NO ;                  % Living Area for Officers (ft^2)
ADL      = ACOXO + ADO ;            % Living Deck Area (Deckhouse) (ft^2)
ADM      = .05*(ADPR + ADL) ;       % Maintenance (ft^2)
AGIE     = SPRSHTge(7)+SPRSHTge(8); % Generator inlet/exhaust X-sect area (ft^2)
% Generator Inlet/Exhaust Area:
AeIE     = NG * AGIE ;              % Inlet/exhaust X-sect area for gen (ft^2)
ADIEe    = 1.4*NDIE*AeIE ;          % Engine Inlet/Exhaust (Deckhouse) (ft^2)
Rep      = 100*ADIEe/ADIEP ;        % The percentage (%) of "Generator Engine
                                    % inlet/exhaust Xsect" to the "Propulsion Engine
                                    % inlet/exhaust Xsect"
ADIE     = (1+Rep/100)*ADIEP ;      % Approximate Deckhouse Inlet/Exhaust Area

ADR      = ADPR+ADL+ADM+ADB+ADIE ;  % Total Required Deckhouse Area
VDR      = HDKd*ADR ;               % Total Required Deckhouse Volume
% Size Deck House:
```

```
ADA       = ADR ;                   % (ft^2)
VD        = VDR ;                   % (ft^3)
                                    % Deckhouse available area & volume must
                                    % be > or = required deckhouse area & volume.
                                    % Assume the area/volume requirements for the
                                    % deckouse are reasonable and set actual deckhouse
                                    % volume VD = to VDR. Therefore, ADA also = to ADR.
% Estimate Total  Ship Volume:
X         = vf*VD ;                 % (ft^3) (this estimate is used for calculations
                                    % until actual total volume is determined.)
% Deckhouse Weight:
if CDHMAT == 1
    RhoDH= .0007;
else
    RhoDH= .001429 ;
end
WDH       = RhoDH * VD ;            % Deckhouse Weight (W150)
%------------------------------------------------------------
% AUXILIARY SYSTEMS
WP600     = Wx(9) ;                 % Mission Outfit Weight (lton)
WP500     = Wx(8) ;                 % Mission Handling/Support Weight (lton)
AHPA      = Ax(3) ;                 % Armament (W500, W600,W700, WF20) (ft^2)
AHPR      = 1.15*AHPA + 1.23*AHPC;  % Payload Hull Area (including access) (ft^2)
kWPAY     = CUM(5);                 % Payload Cruise Electric Power Requirement
%
AHS       = 300 + .0158*NT*9*TS ;   % Hull Stores Area Required (ft^2)
WF31      = NT*9*TS/2240 ;          % Provisions Weight (lton)
WF32      = .0009598*TS*NT ;        % General Stores Weight (lton)
% Potable Water:
WF52      = NT*.15 ;                % Water weight (lton)
VW        = 1.02*WF52*AlphaW ;      % Tank volume (ft^3) (allow 2% for structure)
QDS       = 6.5*NT + 250  ;         % Distiller Rate
% Electrical Power Requirements: (equations from ASSET)
kWRH      = .02*(X-VD)/1000 ;       % UNREP and Handling (kW)
kWH       = .0013*X ;               % Heating (kW)
kWCPS     = CPS*.00026*X ;          % zero if no CPS (kW)
kWV       = .19*(kWH+kWP)+ kWCPS ;  % Ventilation (kW)
kWAC      = .67*(.1*NT+.0015*.47*X+.1*kWP);
                                    % Air Conditioning (assuming 47% of total
                                    % volume is air-conditioned) (kW)
kWB       = .94*NT ;                % Aux Boiler and FW (electric boiler) (kW)
kWL       = .0002053*X ;            % Lighting (kW)
kWSERV    = .35*NT ;                % Services and Work Spaces (kW)
kWF       = .0001*X ;               % Firemain (kW)
kWA       = .22*NT + kWfins ;       % Aux Machinery (kW)
% Aux Steam: (electric aux boiler)
QHS       = 15*NT ;                 % Hotel Steam
W517      = .0013*(QHS + QDS) ;     % W517 (lton)

WCPS      = CPS*30 ;                % CPS Weight (lton) , zero if no CPS
                                    % (WCPS=30.0 lton, CPS not installed = 0 lton)
VSEW      = 2*NT ;                  % Sewage Tank Volume (ft^3)
VAUX      = 1.2*VMB ;               % Aux Systems Volume (ft^3)
WAUX      = (.000772*X^1.443+5.14*X+6.19*X^.7224+377*NT+2.74*PI)*10^-4+113.8;
                                    % Aux Systems Weight (lton)
W5        = WAUX + WP500+ W517 + W593 + W598 + WCPS ;
                                    % Group 500 Weight (lton)
%------------------------------------------------------------
% SHIP SERVICE GENERATORS
% Required Loads:
kWNP      = kWP+kWS+kWL+kWM+kWH+kWV+kWAC+kWB+kWF+kWRH+kWA+kWSERV;
                                    % Non-Payload Functional Load (kW)
kWMFL     = kWPAY + kWNP ;          % Maximum Functional Load (kW)
kWMFLM    = 1.2*1.2*kWMFL ;         % MFL with Margins (kW)
kW24      = .5*(kWMFL-kWP-kWS)+.8*(kWP+kWS);
                                    % 24 hour Electrical Load (kW)
kW24AVG   = 1.2*kW24 ;              % 24 hr Load with Margin (design) (kW)
kWG       = SPRSHTge(5)*0.74568247 ; % Generator power (each generator) (kW)
FRG       = SPRSHTge(6)/0.74568247 ; % Generator fuel rate (lb/(kW.hr))
% Electrical Power Balance:
kWGREQ    = kWMFLM/((NG-1)*.9) ;    % Installed Electrical Power required
                                    % per generator (kW)
ERRKW     = 100*(kWG - kWGREQ)/kWGREQ ;
                                    % Error(%): Negative error means not enough
                                    % installed electrical power.
                                    % CONSTRAINT (ERRKW >= 0)
W3        = 50+.03214*NG*kWG ;      % Electrical Plant Weight (W300) (lton)
% Generator Fuel Rate
f1e       = 1.04 ;                  % Margin for instrumentation and
                                    % machinery differences, f(Pe/PI)
```

```
FRGSP     = f1e * FRG ;              % Specified fuel rate (lb/(kW.hr))
FRGAVG    = 1.05*FRGSP  ;            % Average fuel rate allowing for plant
                                     % deterioration (lb/(kW.hr))
AHIEe     = 1.4*NHeIE*AeIE ;         % Engine Inlet/Exhaust (Hull)
%-----------------------------------------------------------
% FUEL
TPA       = .95 ;                    % Tailpipe allowance for shallow tanks
WFP       = WBP/TPA ;                % Propulsion Fuel Tank Weight (lton)
VFP       = 1.02*1.05*AlphaF*WFP ;   % Propulsion Fuel Tank Volume (ft^3)
                                     % (allow 2% for tank structure and 5% for expansion)
WBe       = (E/Ve)*(kW24AVG*FRGAVG)/2240;
                                     % Burnable electrical endurance fuel weight (lton)
WFe       = WBe/TPA ;                % Include Tailpipe Allowance
VFe       = 1.02*1.05*AlphaF*WFe;    % Electrical Fuel Tank Volume (ft^3) (allow 2% for
                                     % tank structure and 5% for expansion)
% Total ship fuel(DFM);
WF41      = WFP + WFe ;              % (lton)
VF        = VFP + VFe ;              % (ft^3)
%-----------------------------------------------------------
% HULL GEOMETRY
% Minimum Depth at Station 10 determined by:
D10MIN    = max([HMB Ndecks*HDK + BILGE LWL/15]) ;
                                     % LWL/15 :  Logitudinal Strength Criteria
D10x      = D10C* D10MIN ;           % Depth at Station 10
% Calculate Cubic Number (CN):
CN        = LWL*B*D10x/10^5 ;
% Weights:
W164      = Wx(5) ;                  % Armor Weight (lton)
W165      = Wx(6) ;                  % Sonar Dome/Appendages Weight (structure) (lton)
WP        = CUM(1) ;                 % Total Payload Weight (lton)
WOFP      = .8*(NT-9.5) ;            % Personnel-related (lton)
W6        = WOFH + WOFP + WP600 ;    % Group 600 Weights (Outfit and Furnishings)
WBH       = CHMAT*(1.68341*CN^2 + 167.1721*CN - 103.283) ;
                                     % Hull (110-140, 160, 190) (lton)
W180      = .0675*WBM + .072*(W3 + W4 + W5 + W7);
                                     % Foundations (lton)
W1        = WBH + WDH + W171 + W180 + W165 + W164 ;
                                     % Total Group 100 Weight (Structure)
% Hull Area/Volume Requirements:
AHAB      = 50 ;                     % Habitability Allowance (ft^2/man)
AHL       = (AHAB+LWL/100)*NT-ADL ;  % Hull Living Deck Area (ft^2)
AHSF      = 2500*CN ;                % Hull Ship Functions (ft^2)
VBAL      = CBVC*VF ;                % Clean Ballast (ft^3):
VTK       = VF + VHF + VLO + VW + VSEW + VWASTE + VBAL ;
                                     % Total Tankage (ft^3)
AHR       = AHPR + AHL + AHS + AHSF + AHIEP + AHIEe ;
                                     % Total Required Hull Area (ft^2)
VHR       = HDKh*AHR + VTK + VMB + VAUX ;
                                     % Total Required Hull Volume (ft^3)
ATR       = AHR + ADR ;              % Total Required Area (ft^2)
VTR       = VDR + VHR ;              % Total Required Volume (ft^3)
%-----------------------------------------------------------
% WEIGHT BALANCE
WM24      = WM*(W1+W2+W3+W4+W5+W6+W7);
                                     % Weight margin (Future Growth) (lton)
WLS       = (W1+W2+W3+W4+W5+W6+W7)+WM24 ;
                                     % Lightship (lton)
WF10      = (236*NE+400*(NO+1))/2240 ;
                                     % Crew (lton)
WT        = WLS+WF41+WF42+WF20+WF46+WF52+WF31+WF32+WF10 ;
                                     % Total Weight (lton)
WFL       = WP/FP;                   % Full Load Weight (lton)
DELTAFL   = WFL ;                    % Full Load Displacement (equal to full load weight)
ERRWEIGHT= 100*(DELTAFL-WT)/WT;      % Weight Error (%)
                                     %  (if  this  value  nagative,  change  Payload  Weight
Fraction, FP)
%-----------------------------------------------------------
% CHECK HULL PARAMETERS
CDELTAL   = DELTAFL/(LWL/100)^3  ;   % Calculate Displacement to Length Ratio (lton/ft^3)
                                     % Typical range: 45 - 65, Reference:
                                     % "Hydrodynamics in Ship Design"
                                     % by Saunders, SNAME 1957 Vol II (pg 466)
                                     % CONSTRAINT !!!
VFL       = DELTAFL*AlphaSW ;        % Volume at LWL (ft^3)
CV        = VFL/LWL^3 ;              % Volumetric Coefficeient
T         = VFL/(CP*CX*LWL*B) ;      % Draft
CBT       = B/T ;                    % Beam to Draft Ratio:
                                     % Typical Range: 2.8-3.7
                                     % CONSTRAINT !!!
% Must satisfy sheer line criteria: Deck endge must be above water at 25 degree heel
```

```
D10SL    = .21*B+T ;                   % D10SL < or = D10x
                                       % If D10SL > D10x, must increase D10C
                                       % CONSTRAINT !!!
D0MIN    = 1.011827*T-6.36215*10^-6*LWL^2+2.780649*10^-2*LWL+T ;
D20MIN   = .014*LWL*(2.125+1.25*10^-3*LWL)+T ;
% Update Depths at Stations 0, 10, 20 based on sheer line criteria and D10x:
% D0e  must be > = D0MIN               CONSTRAINT !!!
% D10e must be > = D10x                CONSTRAINT !!!
% D20e must be > = D20MIN              CONSTRAINT !!!
D0       = D0e;
D10      = D10e;
D20      = D20e ;
%------------------------------------------------------------
% VOLUME BALANCE
% Criteria: Available hull volume must be  > or = Required hull volume
% Available arrangeable hull area must be > or = Required arrangeable hull area
VHUV     = VFL ;                       % Underwater Hull Volume (ft^3)
VHAWR    = VHR - VFL ;                 % Above water Volume Required (ft^3)
F0       = D0-T ;                      % Freeboard, Station 0  (ft)
F10      = D10-T ;                     % Freeboard, Station 10 (ft)
F20      = D20-T ;                     % Freeboard, Station 20 (ft)
APRO     = LWL*(F0+4*F10+F20)/6 ;      % Projected Area (ft^2)
FAV      = APRO/LWL ;                  % Average Freeboard (ft)
DAV      = FAV + T ;                   % Average Depth (ft)
ff       = .714599 + .18098*(DAV/T) - .018828*(DAV/T)^2;
ff       = max([ff 1]) ;               % Flare factor
VHAWA    = LWL*B*FAV*CW*ff ;           % Above Water Hull Volume Available (ft^3)
VHA      = VHUV + VHAWA ;              % Hull volume available (ft^3)
AHA      = (VHA-VTK-VMB-VAUX)/HDKh;    % Available Hull Arrangeable Area (ft^2)
% Area/Volume Error:
VTA      = VD + VHA ;                  % (ft^3)
ATA      = ADA + AHA ;                 % (ft^2)
ERRVOL   = 100*(VTA-VTR)/VTR ;         % CONSTRAINT (ERRVOL >= 0)
ERRAREA  = 100*(ATA-ATR)/ATR ;         % CONSTRAINT (ERRAREA >= 0)
% If there is a volume or area error, iterate D10, D0, D20, or change LWL,
% B, CP,  etc.                           CONSTRAINT !!!
%------------------------------------------------------------
% RESISTANCE
CB       = CP*CX ;                     % Block Coefficient
SS       = LWL*(2*T+B)*CX^.5*(.4530+.4425*CB-.2862*CX-.003467*B/T+.3696*CW) ;
                                       % Wetted Surface Area (From PNA sec 8.12)
LR       = LWL*(1-CP+.06*CP*.01*LCB/(4*CP-1));
k1          =  .93+.4871*(B/LWL)^1.0681*(T/LWL)^.4611*(LWL/LR)^.1216*(LWL^3/VFL)^.3649*(1-
CP)^-.6042;
CA       = .006*(LWL+100)^-.16-.00205 ;
                                       % Correlation Allowance (From PNA sec 8.12)
V        = linspace(0+eps,50) ;
FnV      = 1.69*V/(g*LWL)^.5 ;         % Froude Number
RNV      = LWL*1.69*V/NuSW  ;          % Reynolds #
CFV      =.075./(log10(RNV)-2).^2;     % Frictional Resistance Coefficient
RFV      = .5*(RhoSW*SS*(1.69*V).^2.*(CA+k1*CFV)) ;
                                       % Frictional Resistance (lbf)
FnVS     = 1.69*VS/(g*LWL)^.5 ;        % Froude Number
RNVS     = LWL*1.69*VS/NuSW  ;         % Reynolds #
CFVS     =.075./(log10(RNVS)-2)^2;     % Frictional Resistance Coefficient
RFVS     = .5*(RhoSW*SS*(1.69*VS)^2*(CA+k1*CFVS));
                                       % Frictional Resistance (lbf) (at VS) ***

FnVe     = 1.69*Ve/(g*LWL)^.5 ;        % Froude Number
RNVe     = LWL*1.69*Ve/NuSW  ;         % Reynolds #
CFVe     =.075./(log10(RNVe)-2)^2;     % Frictional Resistance Coefficient
RFVe     = .5*(RhoSW*SS*(1.69*Ve)^2*(CA+k1*CFVe));
                                       % Frictional Resistance (lbf) (at Ve) ***
VFn4     = .4 *(g*LWL)^.5/1.69 ;       % (knt) for Fn <0.4
VFn55    = .55*(g*LWL)^.5/1.69 ;       % (knt) for Fn <0.55

iE       = 125.67*B/LWL-162.25*CP^2+234.32*CP^3+.1551*(.01*LCB)^3;
%
if  B/LWL < .11
    C4   = .2296*(B/LWL)^0.33333333333333333;
elseif B/LWL < .25
    C4   = B/LWL;
else
    C4   = .5-.0625*(LWL/B);
end
%
C1Lo     = 2223105*C4^3.7861*(T/B)^1.0796*(90-iE)^-1.3757 ;
                                       % for Fn <0.4
C1Hi     = 6919.3*CX^-1.3346*(VFL/LWL^3)^2.0098*((LWL/B)-2)^1.4069 ;
                                       % for Fn>0.55
```

```
C2        = 1 ;                    % sonar dome drag accounted for elsewhere
AT        = B*T*CX*.3 ;            % U/W transom area appox!!!
C3        = 1-.8*AT/(B*T*CX) ;
%
if  CP < 0.8
    C5   = 8.0798*CP-13.8673*CP^2+6.9844*CP^3;
else
    C5   = 1.7301-.7067*CP;
end
%
m1Lo      = .01404*LWL/T-1.7525*(VFL^0.33333333333333333)/LWL-4.7932*B/LWL-C5;
                                   % for Fn <0.4
m1Hi      = -7.2035*(B/LWL)^.3269*(T/B)^.6054 ;
                                   % for Fn>0.55
d         = -.9;
%
if  LWL^3/VFL < 512
    C6   = -1.69385;
elseif LWL^3/VFL < 1727
    C6   = -1.69385 + (LWL/VFL^0.33333333333333333-8)/2.36;
else
    C6   = 0;
end
%
m2V       = C6*.4*exp(-.034*FnV.^-3.29);
m2VS      = C6*.4*exp(-.034*FnVS^-3.29);
m2Ve      = C6*.4*exp(-.034*FnVe^-3.29);
m2VFn4    = C6*.4*exp(-.034 *.4^-3.29);
m2VFn55   = C6*.4*exp(-.034*.55^-3.29);
%
if LWL/B <12
    lambda = 1.446*CP-.03*LWL/B ;
else
    lambda = 1.446*CP-.36 ;
end
%
RWLoV     = C1Lo*C2*C3*2240*DELTAFL*exp(m1Lo*FnV.^d+m2V.*cos(lambda*FnV.^-2));
                                   % for Fn <0.4
RWHiV     = C1Hi*C2*C3*2240*DELTAFL*exp(m1Hi*FnV.^d+m2V.*cos(lambda*FnV.^-2));
                                   % for Fn>0.55
RWLoVFn4 = C1Lo*C2*C3*2240*DELTAFL*exp(m1Lo* .4^d+m2VFn4 *cos(lambda *.4^-2));
RWHiVFn55= C1Hi*C2*C3*2240*DELTAFL*exp(m1Hi*.55^d+m2VFn55*cos(lambda*.55^-2));
RWMidV    = RWLoVFn4+(10*FnV-4)*(RWHiVFn55-RWLoVFn4)/1.5 ;
RWV       = [];                    % Wave Making Resistance (lbf) ***
for i = 1:length(V)
    if  V(i) <= VFn4
        RWV(i)= RWLoV(i);
    elseif V(i) >= VFn55
        RWV(i)= RWHiV(i);
    else
        RWV(i)= RWMidV(i);
    end
end
                                   % Wave Making Resistance (lbf) (at VS)***
if  FnVS <= .4
    RWVS = C1Lo*C2*C3*2240*DELTAFL*exp(m1Lo*FnVS^d+m2VS*cos(lambda*FnVS^-2));
elseif FnVS >= .55
    RWVS = C1Hi*C2*C3*2240*DELTAFL*exp(m1Hi*FnVS^d+m2VS*cos(lambda*FnVS^-2));
else
    RWVS = RWLoVFn4+(10*FnVS-4)*(RWHiVFn55-RWLoVFn4)/1.5;
end
%
if  FnVe <= .4
    RWVe = C1Lo*C2*C3*2240*DELTAFL*exp(m1Lo*FnVe^d+m2Ve*cos(lambda*FnVe^-2));
elseif FnVe >= .55
    RWVe = C1Hi*C2*C3*2240*DELTAFL*exp(m1Hi*FnVe^d+m2Ve*cos(lambda*FnVe^-2));
else
    RWVe = RWLoVFn4+(10*FnVe-4)*(RWHiVFn55-RWLoVFn4)/1.5;
end
RTV       = RFV + RWV ;            % Bare Hull Ship Resistance (lbf) ***
RTVS      = RFVS + RWVS ;          % Bare Hull Ship Resistance (lbf) (at VS)***
RTVe      = RFVe + RWVe ;          % Bare Hull Ship Resistance (lbf) (at Ve)***

AW        = 1.05*B*(D10-T+NDIE*HDKd);% Ship frontal area
                                   %(+ 5% for masts, equipment, etc.):
%------------------------------------------------------------
% STABILITY
% Criteria: Ensure intact stability (GM > 0 ft)
% Maintain proper transverse dynamic stability (GM/B = 0.09 - 0.122)
%
```

```
% VCGs:
VCGP      = CUM(3);                  % (ft) Payload VCG
VCGVP     = CUM(4);                  % Variable Payload VCG
          % Calculate Light Ship Weight Group Moments (lton.ft):
VCG1      = .51*D10;                 P1       = WBH *VCG1;
VCG2      = D10+1.5*HDKd;            P2       = WDH *VCG2;
VCG3      = .68*D10 ;                P3       = W180*VCG3;
VCG4      = 2.65*D10 ;               P4       = W171*VCG4;
P100      = P1+P2+P3+P4;             VCG100   = P100/W1;
VCG5      = .5*D10 ;                 P5       = WBM *VCG5;
VCG6      = .19*T+3.9 ;              P6       = WST *VCG6;
VCG7      = VCG237 ;                 P7       = W237*VCG7;
P200      = P5+P6+P7;                VCG200   = P200/W2;
VCG8      = .6*D10 ;                 P8       = W3  *VCG8;
VCG9      = D10 ;                    P9       = WIC *VCG9;
VCG10     = .5*D10 ;                 P10      = WCC *VCG10;
VCG11     = VCG498 ;                 P11      = W498*VCG11;
VCG12     = .9*(D10-7.4) ;           P12      = WAUX*VCG12;
VCG13     = .5*HMB ;                 P13      = W517*VCG13;
VCG14     = .805*D10 ;               P14      = WOFH*VCG14;
VCG15     = 8+.71*D10 ;              P15      = WOFP*VCG15;
P1to15    = P1+P2+P3+P4+P5+P6+P7+P8+P9+P10+P11+P12+P13+P14+P15;
PWG       = P1to15 + WP*VCGP - WVP*VCGVP ;
VCGLS     = PWG/(W1+W2+W3+W4+W5+W6+W7);
KGLS      = VCGLS ;                  % Light Ship KG (ft)
% Load VCGs:
          % Calculate Variable Load Weight Group Moments:
VCG16     = .7*D10 ;                 P16      = WF10*VCG16;
VCG17     = .55*D10 ;                P17      = WF31*VCG17;
VCG18     = .65*D10 ;                P18      = WF32*VCG18;
VCG19     = 6 ;                      P19      = WF41*VCG19;
VCG20     = 10 ;                     P20      = WF42*VCG20;
VCG21     = .35*D10 ;                P21      = WF46*VCG21;
VCG22     = 7.5 ;                    P22      = WF52*VCG22;
PWGL      = (P16+P17+P18+P19+P20+P21+P22) + WVP*VCGVP;
WL        = WF10+WF20+WF31+WF32+WF41+WF42+WF46+WF52 ;
VCGL      = PWGL/WL ;                % Load VCGs(ft)
% Ship Stability Characteristics:
KG        = (WLS*KGLS + WL*VCGL)/WT + KGMARG ;
CIT       = -.497 + 1.44*CW ;
KB        = T*(2.5-CP*CX/CW)/3 ;     % (ft)
BM        = LWL*B^3*CIT/(12*VFL) ;   % (ft) this is an approximation using
                                     % Morrish formula (PNA Vol 1, p. 38)
GM        = KB + BM - KG ;           % (GM > 0 ft)
                                     % CONSTRAINT !!!
CGMB      = GM/B ;                   % (0.09 - 0.122)
                                     % CONSTRAINT !!!
                                     % ***  If GM < 0 ft and/or GM/B not
                                     % within limits, must alter
                                     % LWL, B, CP, CX, D0, D10, D20 until
                                     % limits are achieved.
C         = (.38+.55)/2 ;            % (C = empirical constant = 0.38 - 0.55)
Troll     = C*B/GM^.5 ;              % roll period (sec)
%-----------------------------------------------------------
% PROPULSIVE POWER BALANCE
% Criteria: Installed propulsive power must be > or = Required propulsive power
% Required Propulsive Power to overcome drag due to:
% Bare Hull:
PEBHV     = RTV.*V*1.69*60/33000 ;   % Bare Hull (hp)
PEBHVS    = RTVS*VS*1.69*60/33000 ;
PEBHVe    = RTVe*Ve*1.69*60/33000 ;
% Appendage:
CDAPP     = 2.8*10^-5 ;              % Appendage Drag  Coefficient
PEAPPpV   = LWL*DP*CDAPP*V.^3 ;      % Propellers (hp)
PEAPPpVS  = LWL*DP*CDAPP*VS^3 ;      % Propellers (hp)
PEAPPpVe  = LWL*DP*CDAPP*Ve^3 ;      % Propellers (hp)
%
PEAPPsdV = (.5*CSD*RhoSW*ASD*(1.69*V).^3)*60/33000;
                                     % Sonar Dome (hp)
PEAPPsdVS= (.5*CSD*RhoSW*ASD*(1.69*VS)^3)*60/33000;
                                     % Sonar Dome (hp)
PEAPPsdVe= (.5*CSD*RhoSW*ASD*(1.69*Ve)^3)*60/33000;
                                     % Sonar Dome (hp)
%
PEAPPV    = PEAPPpV + PEAPPsdV ;     % Total Appendage (hp)
PEAPPVS   = PEAPPpVS+ PEAPPsdVS ;    % Total Appendage (hp)
PEAPPVe   = PEAPPpVe+ PEAPPsdVe ;    % Total Appendage (hp)
%
% Air:
PEAAV     = (.5*CAA*RhoA*AW*(1.69*V).^3)*60/33000 ;
```

```
                              % Air (hp)
PEAAVS   = (.5*CAA*RhoA*AW*(1.69*VS)^3)*60/33000 ;
                              % Air (hp)
PEAAVe   = (.5*CAA*RhoA*AW*(1.69*Ve)^3)*60/33000 ;
                              % Air (hp)
% Total Ship Effective Horsepower Required:
PETV     = PEBHV + PEAPPV + PEAAV;  % (hp)
PETVS    = PEBHVS+ PEAPPVS+ PEAAVS; % (hp)
PETVe    = PEBHVe+ PEAPPVe+ PEAAVe; % (hp)

EHPV     = PMF*PETV ;              % (hp)
EHPVS    = PMF*PETVS;              % (hp)
EHPVe    = PMF*PETVe;              % (hp)
%
% Required Shaft Horsepower:
SHPV     = EHPV/PC;                % (hp)
SHPVS    = EHPVS/PC ;              % (hp)
SHPVe    = EHPVe/PC ;              % (hp)
%
PS       = SHPVS ;                 % Sustained Shaft Horsepower
PIREQ    = 1.25*PS ;               % Installed Shaft Horsepower required to
                                   % achieve sustained speed
                                   % (Allows for fouling and sea state) :
                                   % (PI must be > PIREQ)
                                   % CONSTRAINT !!!
ERRPOWER = 100*(PI-PIREQ)/PIREQ ;  % Propulsive Power Error (%)
                                   % ***  If PI <  PIREQ  (ERRPOWER < 0),
                                   % must alter LWL, B,  CP, CX, D0, D10, D20,
                                   % or number or type of proulsion engines
                                   % CONSTRAINT !!!
Pe       = SHPVe ;                 % Actual Endurance Range
PeBAVG   = 1.1*Pe/eta ;            % (hp)
f1       = 1.04 ;                  % Margin for instrumentation and
                                   % machinery differences, f(Pe/PI)
FRSP     = f1*FR ;                 % Specified fuel rate
FRAVG    = 1.05 * FRSP ;           % Average fuel rate allowing for
                                   % plant deterioration (lb/(hp.hr))
Eact     = 2240*WBP*Ve/(PeBAVG*FRAVG) ;
                                   % ***  If Eact  <  E, increase WBP
                                   % (weigth of burnable propulsion fuel)
                                   % ***  If Eact  >> E, decrease WBP
                                   % CONSTRAINT !!!
%------------------------------------------------------------
%VERY SIMPLIFIED COST MODEL (Lead-Ship End Cost only)
LS       = 30 ;                    % Ship Service Life
NS       = 25 ;                    % Total Ship Acquisition
YIOC     = 2005;                   % Initial Operational Capability
RP       = 3;                      % Production Rate

% Inflation:
YB       = 2005;                   % Base Year
RI       = 5;                      % Average Inflation Rate (%) from 1988
FI       = 1;
for iy   = 1:YB-1988
    FI   = FI*(1+RI/100);
end
% Lead Ship Cost-Ship builder Portion(Mdollars):
% Structure
KN1      = .55;
CL1      = .03395*FI*KN1*W1^.772 ;
% + Propulsion
KN2      = 1.2;
CL2      = .00186*FI*KN2*PIBRAKE^.808 ;
% + Electric
KN3      = 1;
CL3      = .07505*FI*KN3*W3^.91 ;
% + Command, Control and Surveilence
KN4      = 2;
CL4      = .10857*FI*KN4*W4^.617;
% + Auxiliary
KN5      = 1.5;
CL5      = .09487*FI*KN5*W5^.782 ;
% + Outfit
KN6      = 1;
CL6      = .09859*FI*KN6*W6^.784 ;
% + Armament
KN7      = 1;
CL7      = .00838*FI*KN7*W7^.987 ;
% + Margin Cost
CLM      = (WM24/(WLS-WM24))*(CL1+CL2+CL3+CL4+CL5+CL6+CL7) ;
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% + Integration/Engineering
% (Lead ship includes detail design engineering for class)
KN8      = 10;
CL8      = .034*KN8*(CL1+CL2+CL3+CL4+CL5+CL6+CL7+CLM)^1.099 ;
% + Ship Assembly and Support
% (Lead Ship includes all tooling, jigs, special facilities for class)
KN9      = 2;
CL9      = .135*KN9*(CL1+CL2+CL3+CL4+CL5+CL6+CL7+CLM)^.839 ;
% = Total Lead Ship Construction Cost: (BCC)
CLCC = CL1+CL2+CL3+CL4+CL5+CL6+CL7+CL8+CL9+CLM;
% + Profit
FPROFIT  = .10;
CLP      = FPROFIT * CLCC ;
% = Lead Ship Price
PL       = CLCC + CLP ;
% + Change Orders
CLCORD   = .12*PL;
% = Total Shipbuilder Portion
CSB      = PL + CLCORD ;
% Lead Ship Cost-Goverment Portion(Mdollars):
% Other Support
CLOTH    = .025*PL ;
% + Program Manager's Growth
CLPMG    = .1*PL ;
% Costed Military Payload
WF23     = Wx(2) ;
WMP      = W4 + W7 + WF20 - WIC - WF23;
NHELO    = 2;
CLMPG    = (.319*WMP+NHELO*18.71)*FI;
% + HM&E GFE (boats, IC)
CLHMEG   = .02*PL;
% + Outfitting Cost
CLOUT    = .04*PL ;
% = Total Goverment Cost
CLGOV    = CLOTH + CLPMG +CLMPG + CLHMEG + CLOUT;
% TOTAL END COST (Mdollars) :
CLEND    = CSB + CLGOV;
COST     = CLEND;
%------------------------------------------------------------
% functions values                  % FUNCTIONAL CONSTRAINTS:
f1  = kWG - kWGREQ ;                % kWG - kWGREQ >= 0
f2  = D10x-D10SL;                   % D10x-D10SL  >= 0,
f3  = GM ;                          % GM > 0         (Ship Stability Characteristics)
f4  = PI-PIREQ ;                    % PI-PIREQ >= 0,
f5  = Eact-E ;                      % Eact-E >= 0 ,          Pseudo-criterion (MIN)
f6  = Ndecks-NHPIE;                 % Ndecks-NHPIE >=0
f7  = Ndecks-NHeIE;                 % Ndecks-NHeIE >=0
f8  = CLB ;                         % 7.5 <= CLB <= 10       Pseudo-criterion (MIN/MAX)
f9  = CBT ;                         % 2.8 <= CBT <= 3.7      Pseudo-criterion (MIN/MAX)
f10 = CDELTAL ;                     % 45 <= CDELTAL <= 65,   Pseudo-criterion (MIN/MAX)
f11 = CGMB ;                        % 0.09 <= CGMB <= 0.122  Pseudo-criterion (MIN/MAX)
                                    % (Ship Stability Characteristics)
%------------------------------------------------------------
c1  = ERRKW ;                       % Criterion (MIN)
c2  = ERRPOWER ;                    % Criterion (MIN)
c3  = ERRVOL  ;                     % Criterion (MAX)
c4  = ERRAREA  ;                    % Criterion (MAX)
c5  = ERRWEIGHT;                    % Criterion (MAX)
c6  = COST  ;                       % Criterion (MIN)
%------------------------------------------------------------
% REFERENCES:
% [1] movi_oscillator.m (MATLAB m-file) (STATNIKOV R.B.)
% [2] STATNIKOV R.B. 2003, MOVI 1.3 Software Package User's Manual.
% [3] MIT FUNCTIONAL SHIP DESIGN SYNTHESIS MODEL
```

APPENDIX G. MATLAB CODE FOR TESTING THE MIT FUNCTIONAL SHIP DESIGN SYNTHESIS MODEL RESULTS

shiptest.m

```
% This file tests the results of MOVI 1.3
% software for the optimization of MIT FUNCTIONAL
% SHIP DESIGN SYNTHESIS MODEL.
%
% Kivanc Ali ANIL, 2004
%
%------------------------------------------------------------
clear, clc
%INPUT
prompt          ={'ENTER THE FILE NAME FOR THE RESULTS'};
def13           = {'vectornumber'};
fname           = inputdlg(prompt,' FILE NAME',1,def13);
filename        = char(fname);
if isempty(filename)==1
    clc;
    return
end
[data, textdata ] = xlsread([filename,'.xls']);


p               = data([7:51],1);
[c1,c2,c3,c4,c5,c6,f1,f2,f3,f4,f5,f6,f7,f8,f9,f10,f11] = ship(p(1),...
    p(2),p(3),p(4),p(5),p(6),p(7),p(8),p(9),p(10),...
    p(11),p(12),p(13),p(14),p(15),p(16),p(17),p(18),p(19),p(20),...
    p(21),p(22),p(23),p(24),p(25),p(26),p(27),p(28),p(29),p(30),...
    p(31),p(32),p(33),p(34),p(35),p(36),p(37),p(38),p(39),p(40),...
    p(41),p(42),p(43),p(44),p(45));
% ------------------------------------------------------------
FUNC            = [f1;f2;f3;f4;f5;f6;f7];
CRIT            = [c1;c2;c3;c4;c5;c6;f8;f8;f9;f9;f10;f10;f11;f11;f5];
% ------------------------------------------------------------
Excel           = actxserver('Excel.Application');
set(Excel, 'Visible' , 1);
Workbook        = invoke(Excel.Workbooks, 'Add');
% ------------------------------------------------------------
L               = length(p);
firstcell       = ['B' '7'];
lastcell        = ['B' num2str(L+6)];
Activesheet     = Excel.Activesheet;
ActivesheetRange= get(Activesheet,'Range',firstcell,lastcell);
set(ActivesheetRange, 'Value', p);
% ------------------------------------------------------------
L               = length(FUNC);
firstcell       = ['F' '7'];
lastcell        = ['F' num2str(L+6)];
Activesheet     = Excel.Activesheet;
ActivesheetRange= get(Activesheet,'Range',firstcell,lastcell);
set(ActivesheetRange, 'Value', FUNC);
% ------------------------------------------------------------
L               = length(CRIT);
firstcell       = ['F' '16'];
lastcell        = ['F' num2str(L+15)];
Activesheet     = Excel.Activesheet;
ActivesheetRange= get(Activesheet,'Range',firstcell,lastcell);
set(ActivesheetRange, 'Value', CRIT);
% ------------------------------------------------------------
funcmovi        =  data([7:13],3);
L               = length(funcmovi);
firstcell       = ['E' '7'];
lastcell        = ['E' num2str(L+6)];
Activesheet     = Excel.Activesheet;
ActivesheetRange= get(Activesheet,'Range',firstcell,lastcell);
set(ActivesheetRange, 'Value', funcmovi);
% ------------------------------------------------------------
critmovi        = data([7:21],5);
L               = length(critmovi );
firstcell       = ['E' '16'];
lastcell        = ['E' num2str(L+15)];
Activesheet     = Excel.Activesheet;
ActivesheetRange= get(Activesheet,'Range',firstcell,lastcell);
set(ActivesheetRange, 'Value', critmovi );
```

```
% -------------------------------------------------------------
ttt1            = 'Comparison of MOVI results and MATLAB results.';
ttt2            = 'This comparison is needed to see the reliability of MOVI results.';
text1           = [cellstr(ttt1);cellstr(ttt2);textdata([2,4],1)] ;
L               = length(text1);
firstcell       = ['A' '1'];
lastcell        = ['A' num2str(L)];
Activesheet     = Excel.Activesheet;
ActivesheetRange= get(Activesheet,'Range',firstcell,lastcell);
set(ActivesheetRange, 'Value', text1);
% -------------------------------------------------------------
text2           = textdata([6:51],1);
L               = length(text2);
firstcell       = ['A' '6'];
lastcell        = ['A' num2str(L+5)];
Activesheet     = Excel.Activesheet;
ActivesheetRange= get(Activesheet,'Range',firstcell,lastcell);
set(ActivesheetRange, 'Value', text2);
% -------------------------------------------------------------
text3           = textdata([6:13],3);
L               = length(text3);
firstcell       = ['D' '6'];
lastcell        = ['D' num2str(L+5)];
Activesheet     = Excel.Activesheet;
ActivesheetRange= get(Activesheet,'Range',firstcell,lastcell);
set(ActivesheetRange, 'Value', text3);
% -------------------------------------------------------------
text4           = textdata([6:21],5);
L               = length(text4 );
firstcell       = ['D' '15'];
lastcell        = ['D' num2str(L+14)];
Activesheet     = Excel.Activesheet;
ActivesheetRange= get(Activesheet,'Range',firstcell,lastcell);
set(ActivesheetRange, 'Value', text4 );
% -------------------------------------------------------------
text5           = [cellstr('MOVI'),cellstr('MATLAB'),cellstr('ERROR')] ;
firstcell       = ['E' '6'];
lastcell        = ['G' '6'];
Activesheet     = Excel.Activesheet;
ActivesheetRange= get(Activesheet,'Range',firstcell,lastcell);
set(ActivesheetRange, 'Value', text5);
firstcell       = ['E' '15'];
lastcell        = ['G' '15'];
Activesheet     = Excel.Activesheet;
ActivesheetRange= get(Activesheet,'Range',firstcell,lastcell);
set(ActivesheetRange, 'Value', text5);
% -------------------------------------------------------------
text6           = cellstr('= E7 - F7') ;
firstcell       = ['G' '7'];
lastcell        = ['G' '13'];
Activesheet     = Excel.Activesheet;
ActivesheetRange= get(Activesheet,'Range',firstcell,lastcell);
set(ActivesheetRange, 'Value', text6);
% -------------------------------------------------------------
text7           = cellstr('= E16 - F16') ;
firstcell       = ['G' '16'];
lastcell        = ['G' '30'];
Activesheet     = Excel.Activesheet;
ActivesheetRange= get(Activesheet,'Range',firstcell,lastcell);
set(ActivesheetRange, 'Value', text7);
% -------------------------------------------------------------
%RESULTS
prompt          ={'ENTER THE FILE NAME FOR THE RESULTS'};
def13           = {[filename,'CHECK']};
fname           = inputdlg(prompt,' FILE NAME',1,def13);
filename2        = char(fname);
if isempty(filename2)==1
    clc;
    return
end
w=pwd;
invoke(Workbook, 'SaveAs', [w,'\',filename2,'.xls']);
```

APPENDIX H. CRITERION VS. CRITERION GRAPHS (MIT MODEL) – 1ST OPTIMIZATION

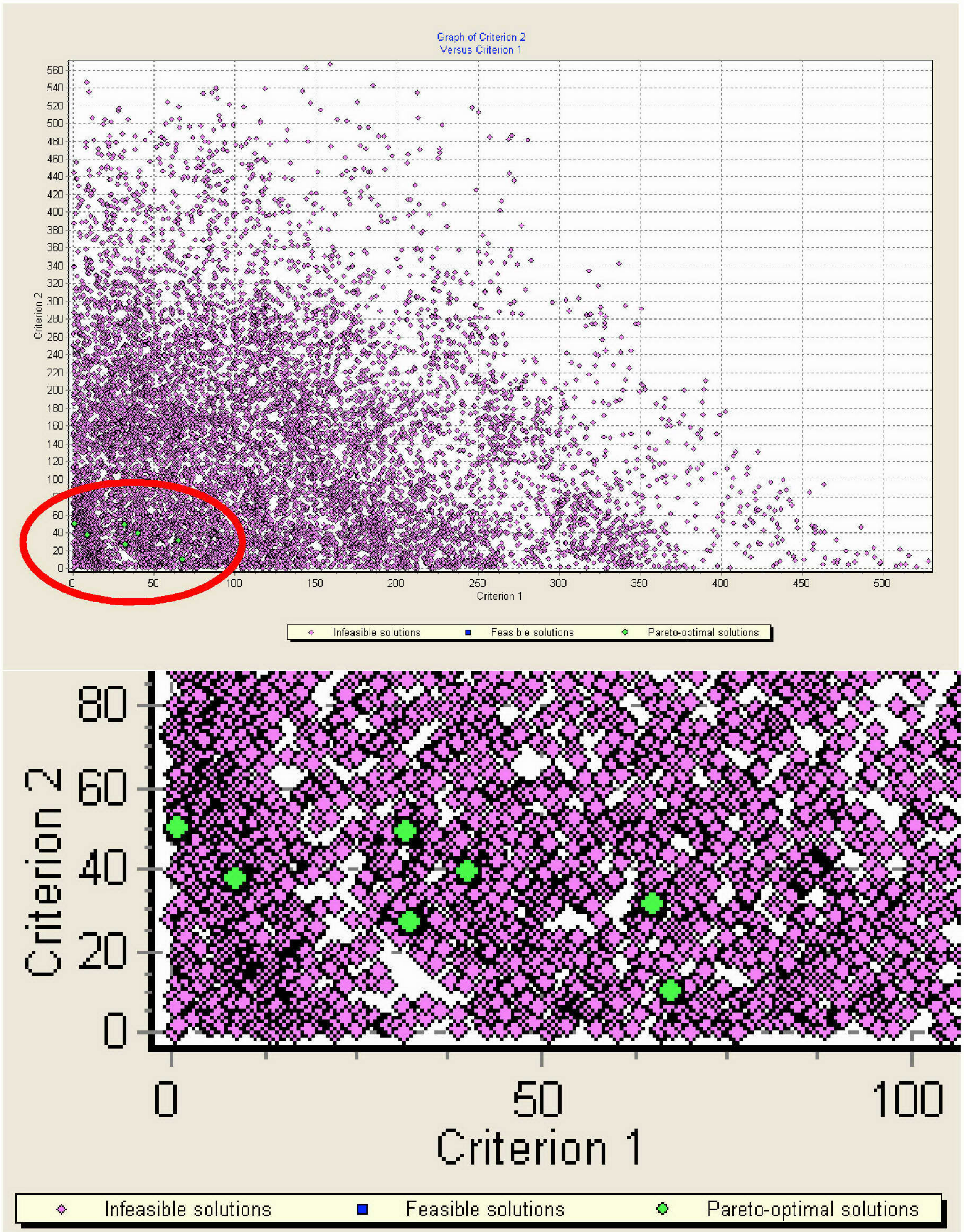

Figure 58 Criterion 1 (Minimized) vs. Criterion 2 (Minimized) – 1st Optimization.

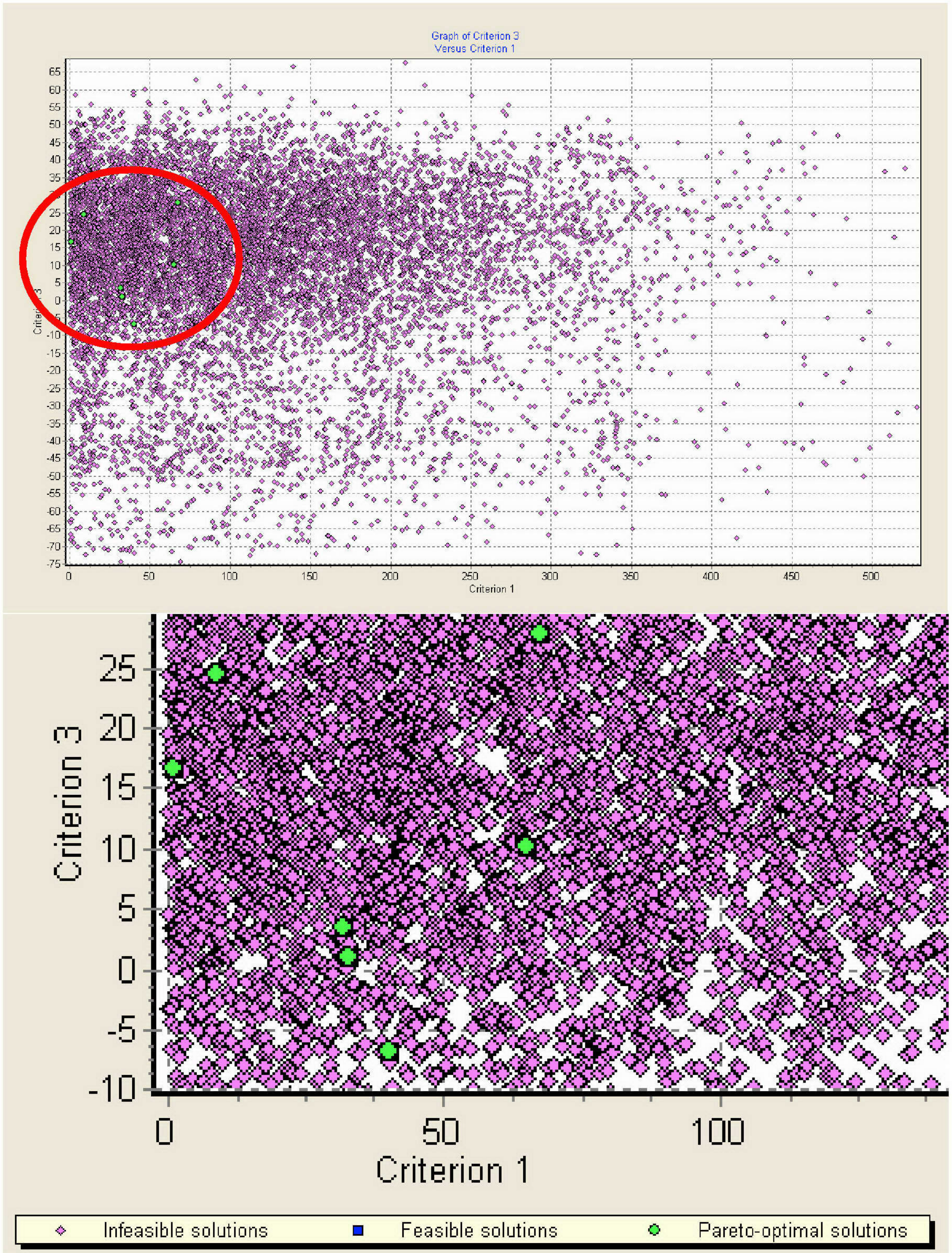

Figure 59 Criterion 1 (Minimized) vs. Criterion 3 (Maximized) – 1st Optimization.

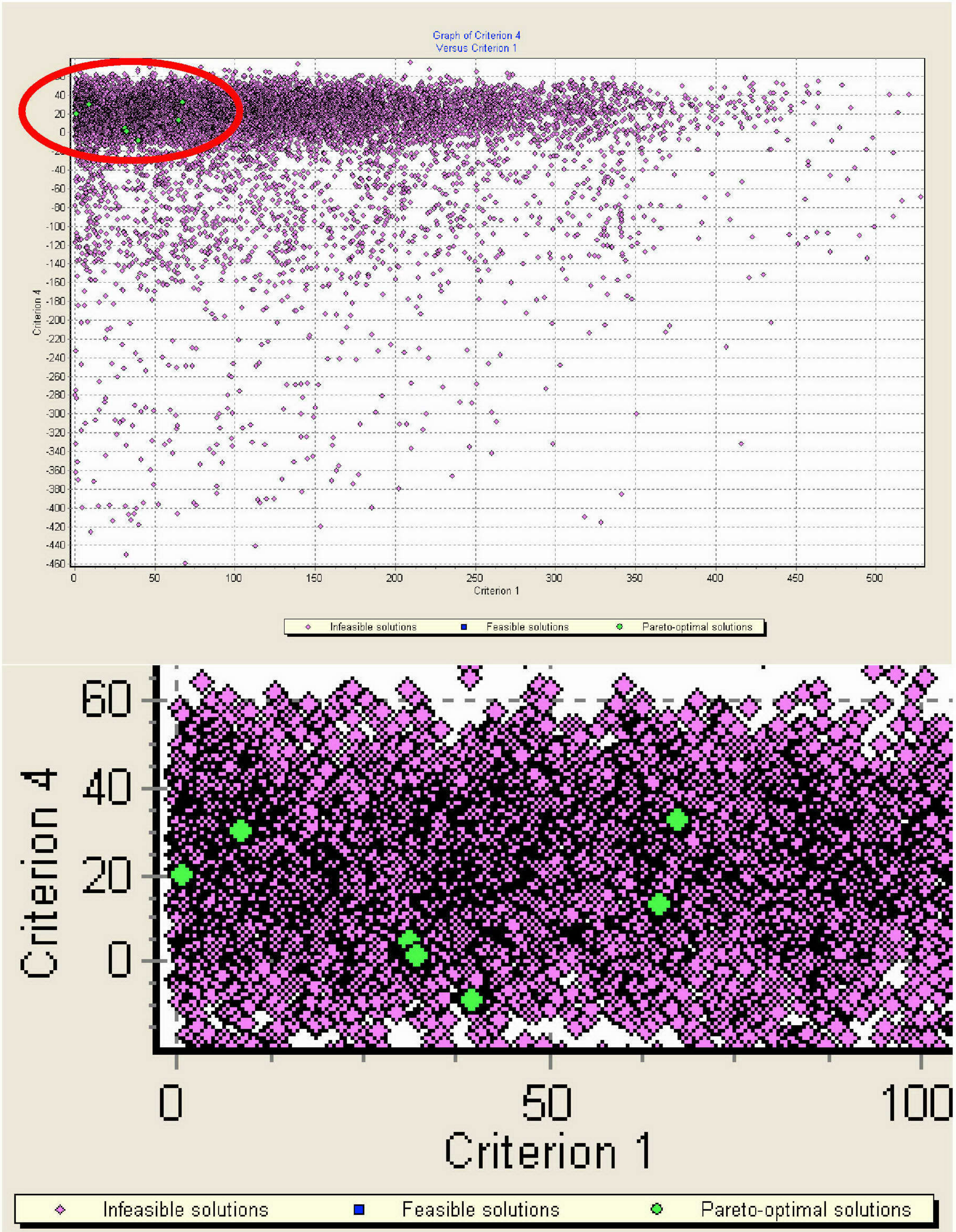

Figure 60 Criterion 1 (Minimized) vs. Criterion 4 (Maximized) – 1st Optimization.

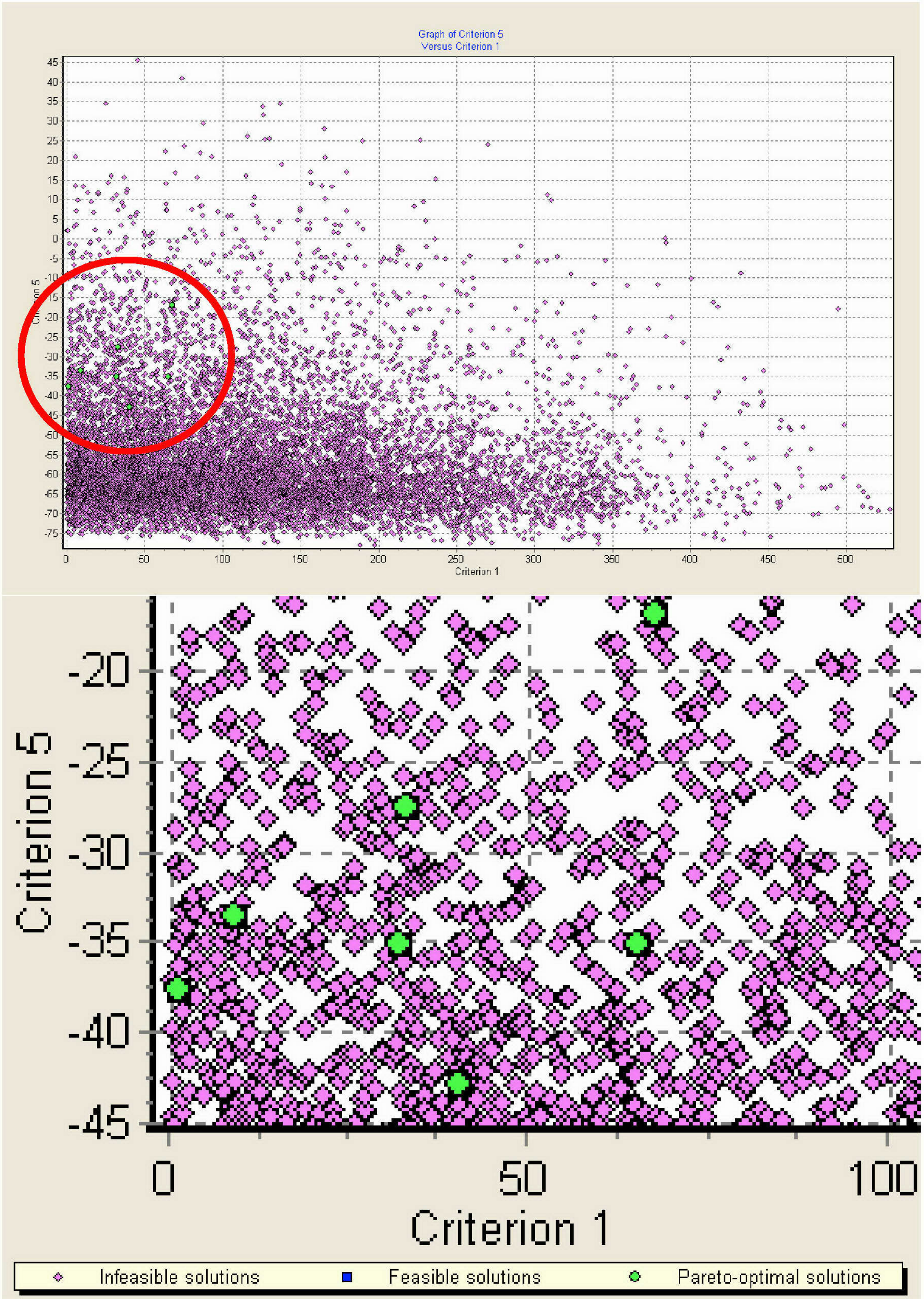

Figure 61 Criterion 1 (Minimized) vs. Criterion 5 (Maximized) – 1st Optimization.

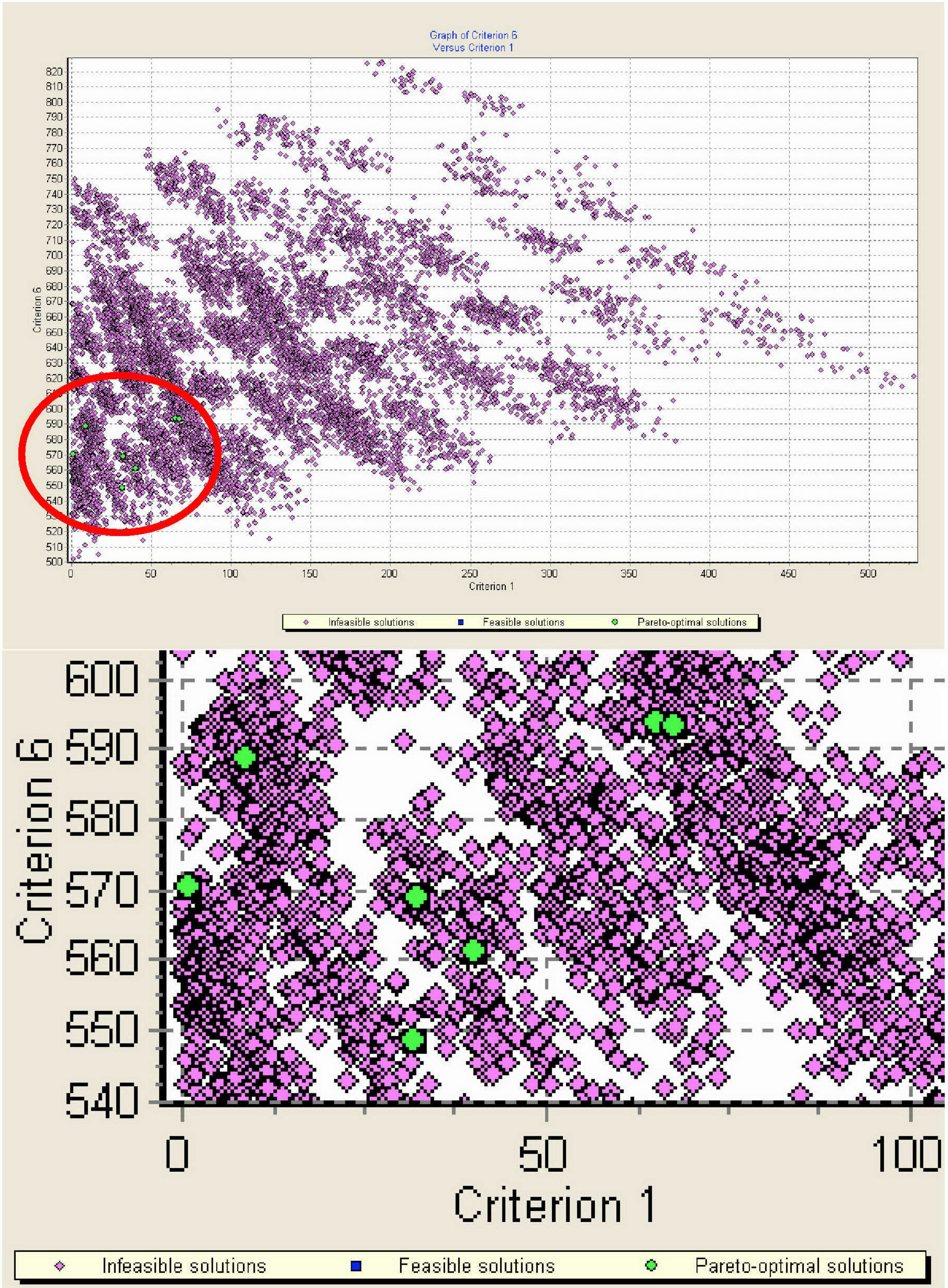

Figure 62 Criterion 1 (Minimized) vs. Criterion 6 (Minimized) – 1st Optimization.

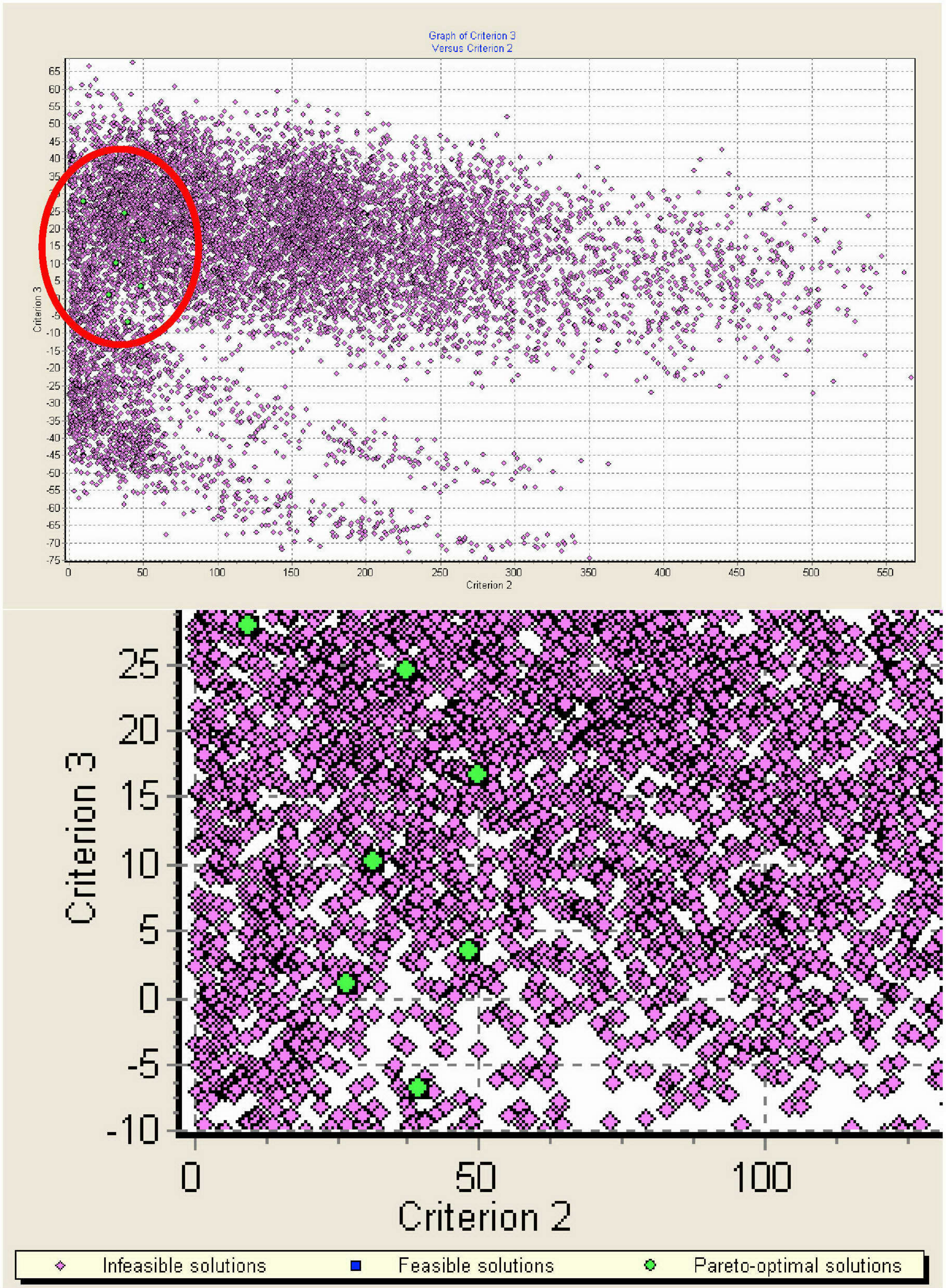

Figure 63 Criterion 2 (Minimized) vs. Criterion 3 (Maximized) – 1st Optimization.

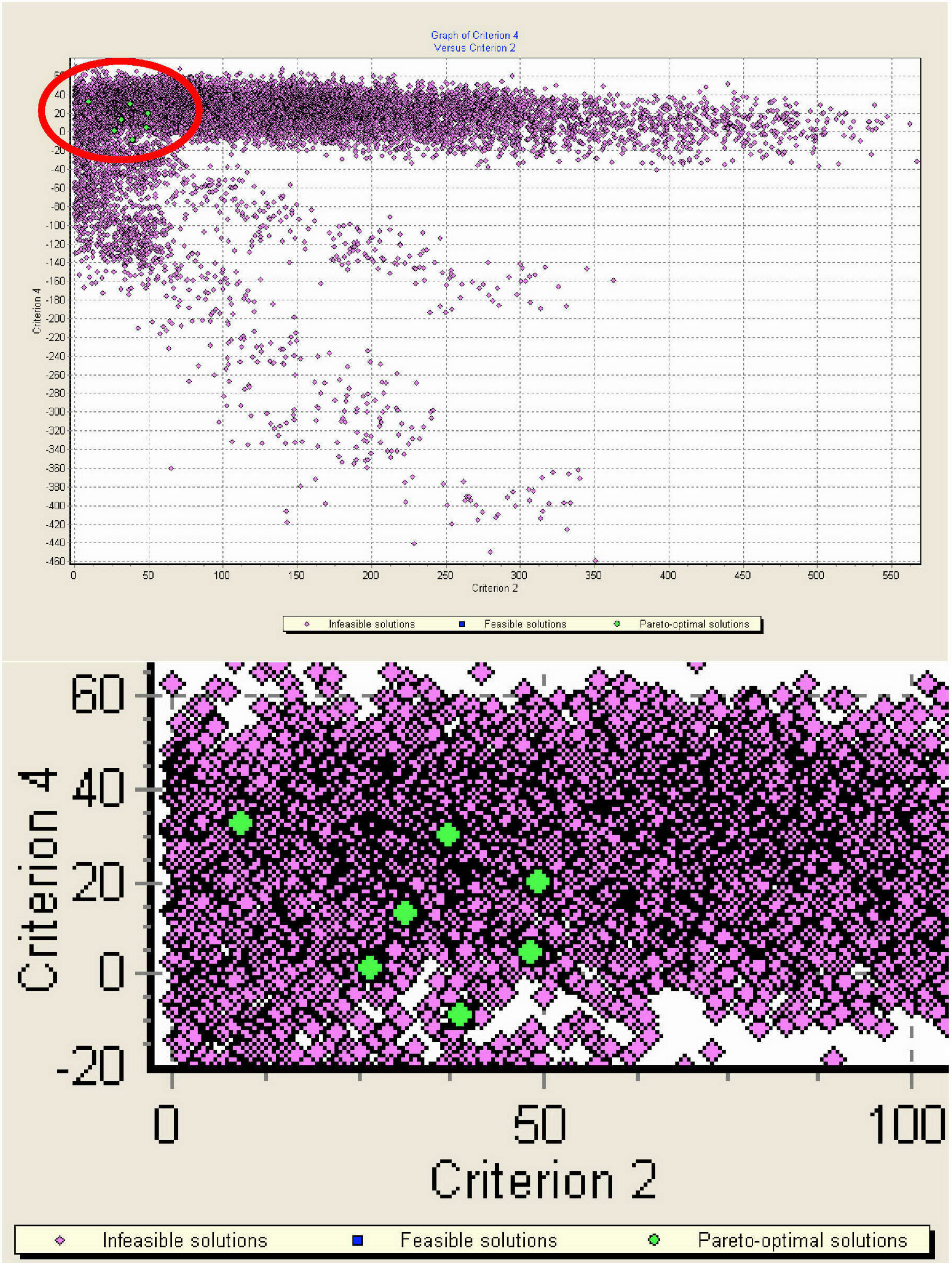

Figure 64 Criterion 2 (Minimized) vs. Criterion 4 (Maximized) – 1st Optimization.

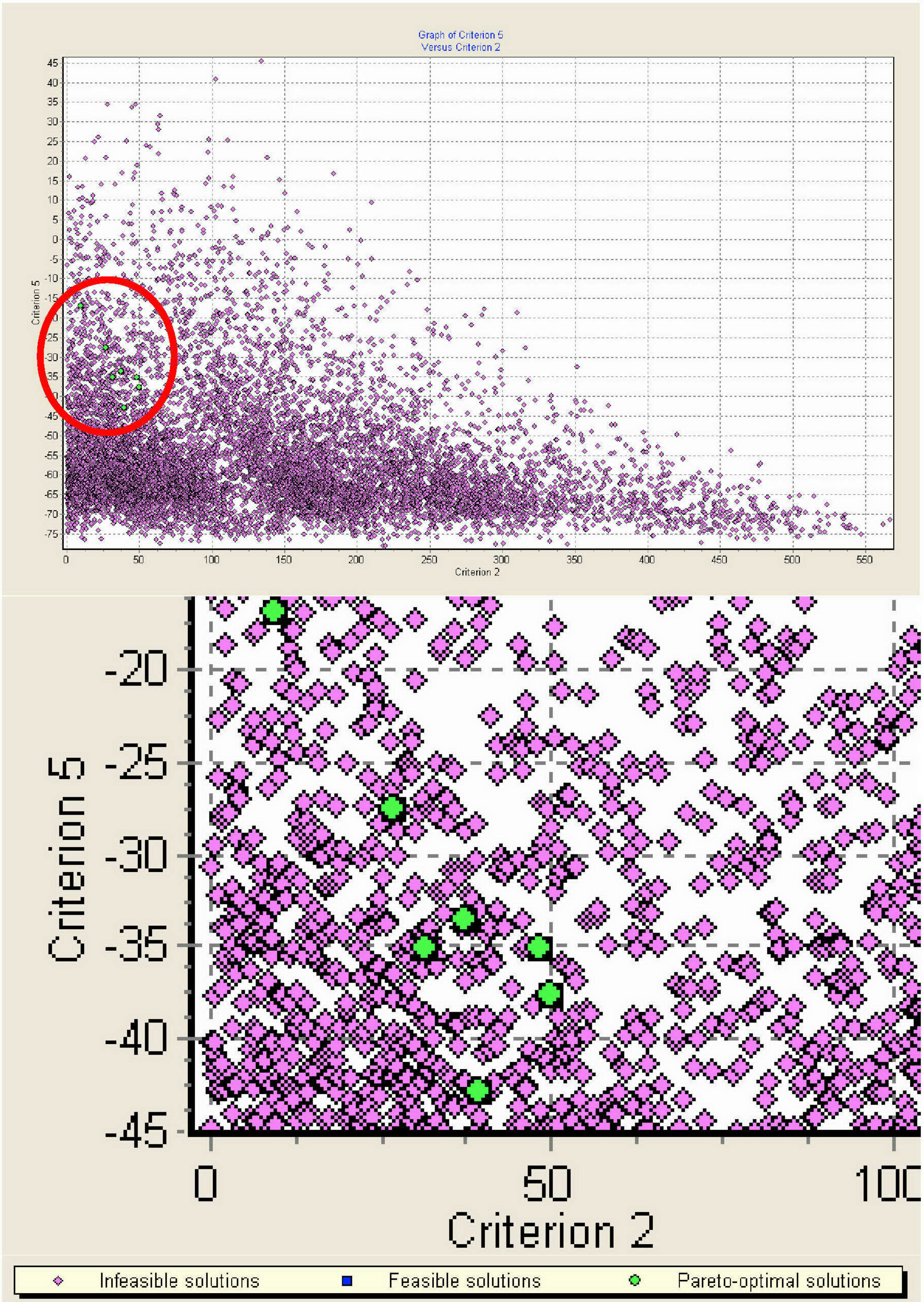

Figure 65 Criterion 2 (Minimized) vs. Criterion 5 (Maximized) – 1st Optimization.

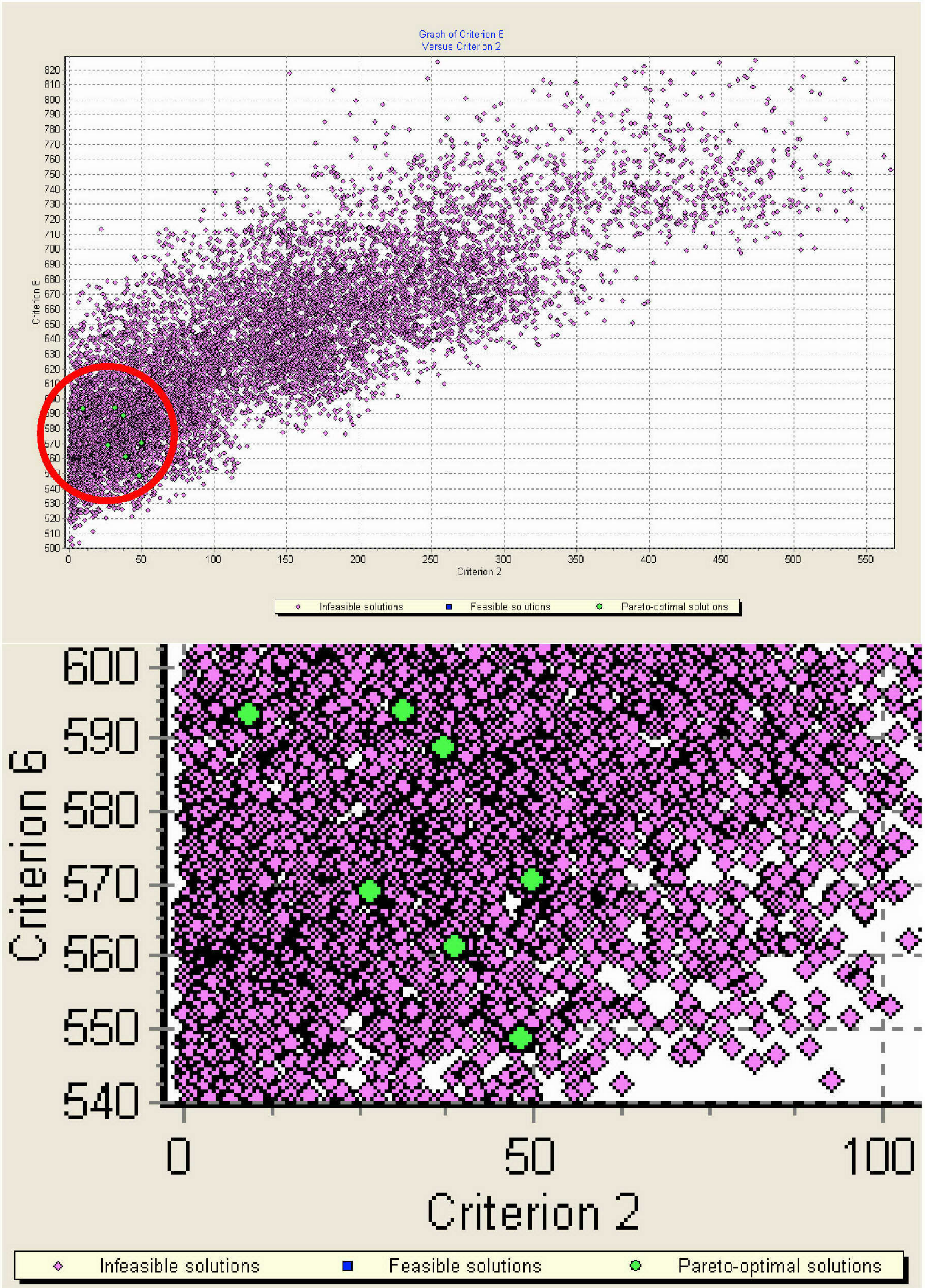

Figure 66 Criterion 2 (Minimized) vs. Criterion 6 (Minimized) – 1st Optimization.

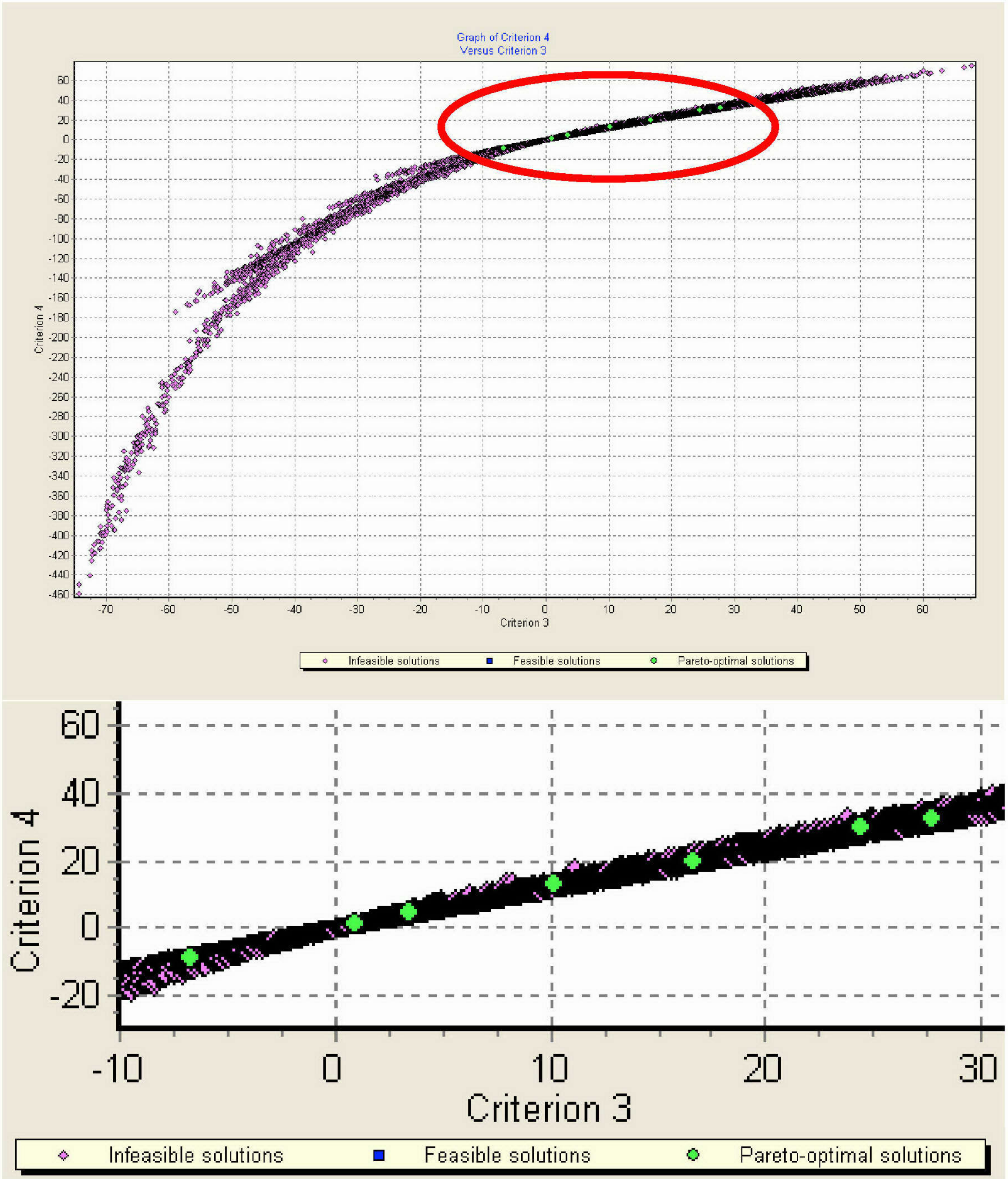

Figure 67 Criterion 3 (Maximized) vs. Criterion 4 (Maximized) – 1st Optimization.

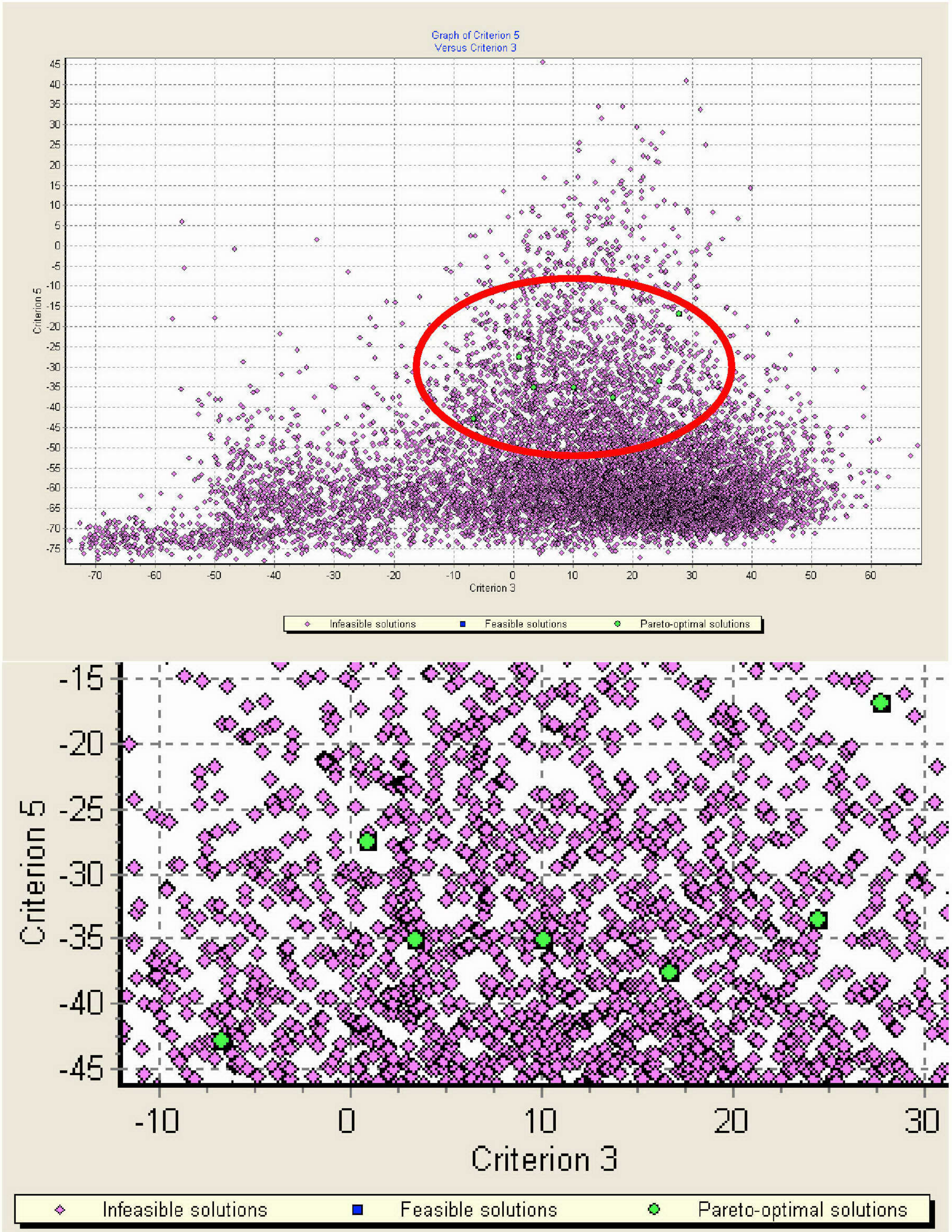

Figure 68 Criterion 3 (Maximized) vs. Criterion 5 (Maximized) – 1st Optimization.

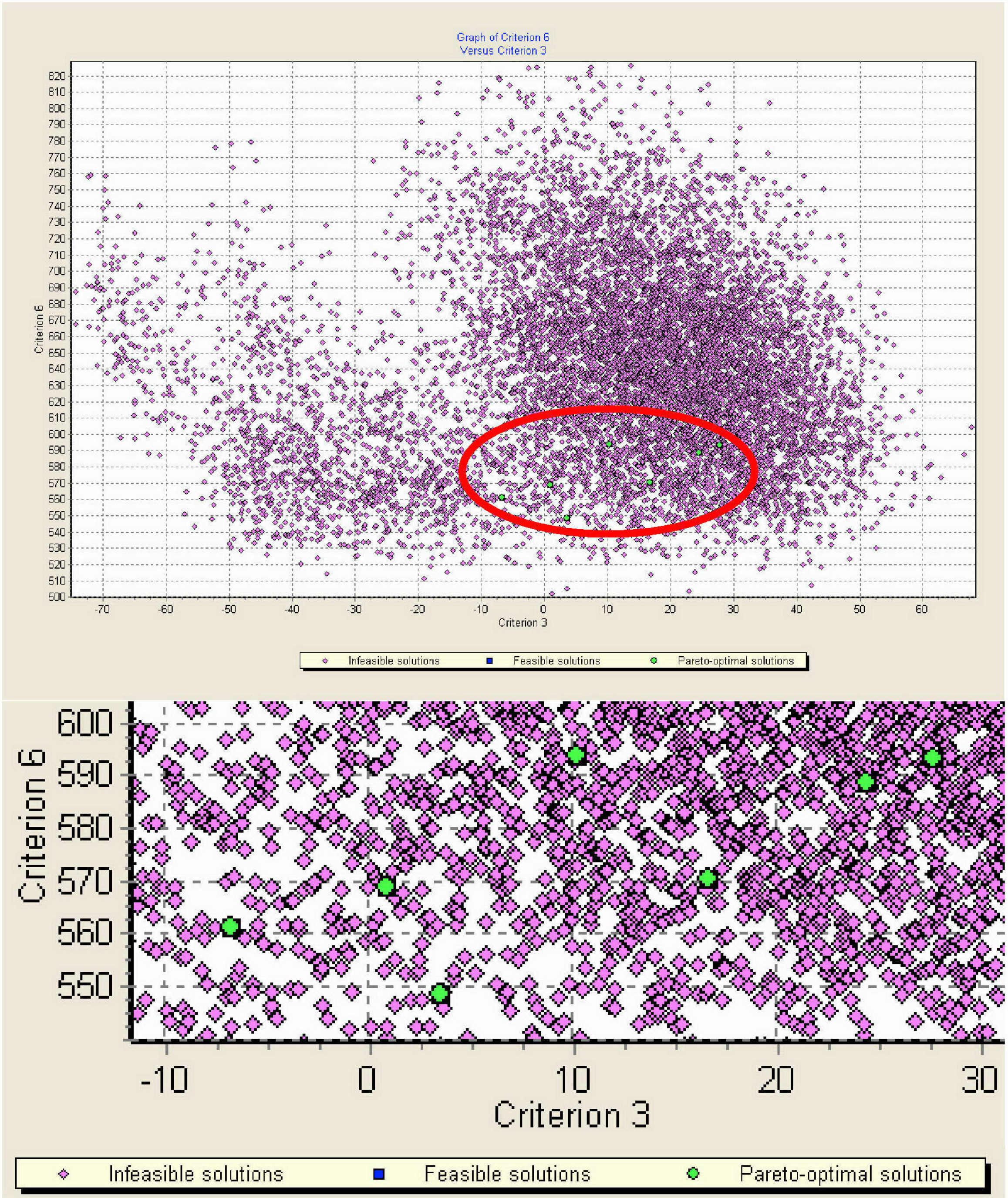

Figure 69 Criterion 3 (Maximized) vs. Criterion 6 (Minimized) – 1st Optimization.

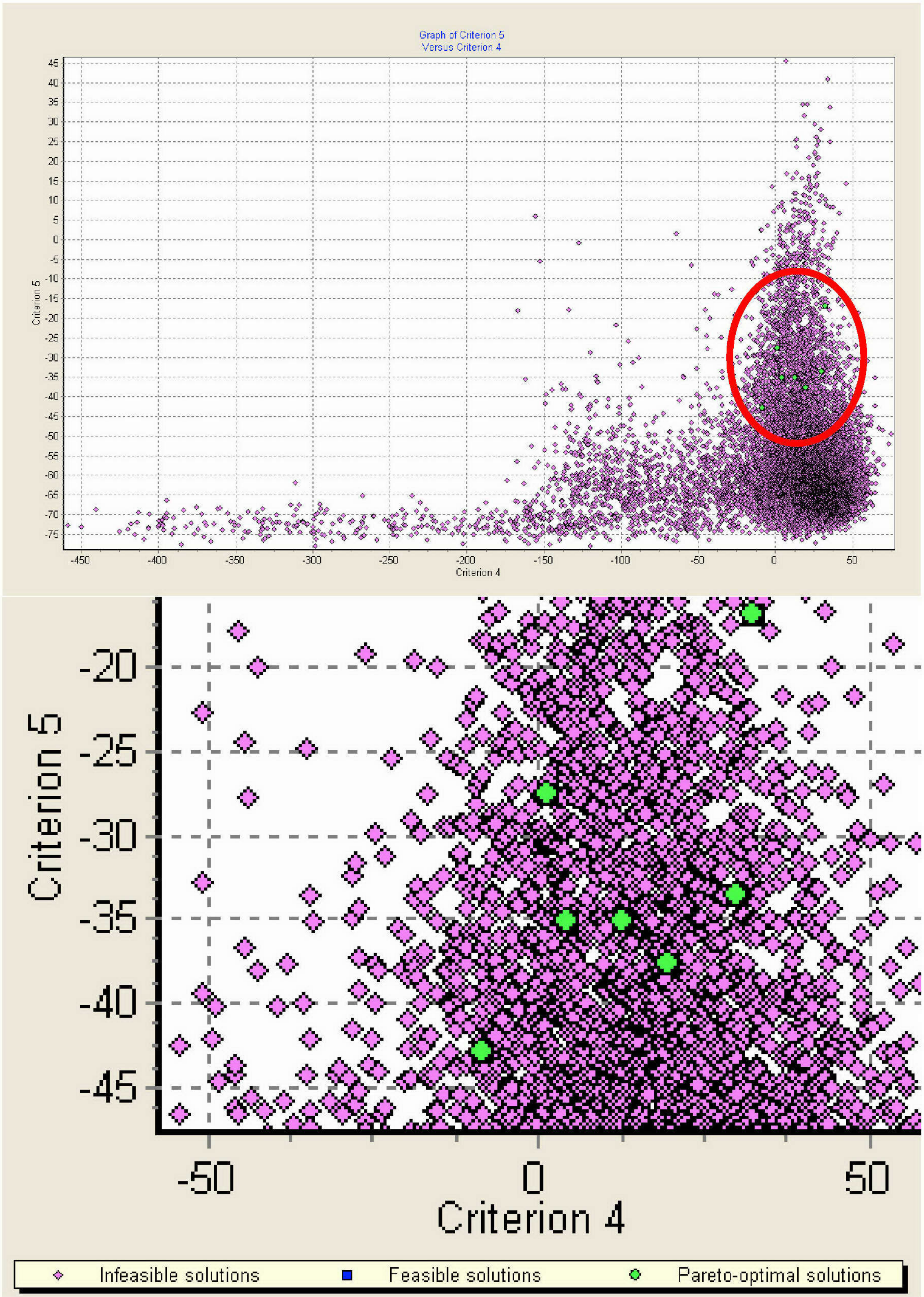

Figure 70 Criterion 4 (Maximized) vs. Criterion 5 (Maximized) – 1st Optimization.

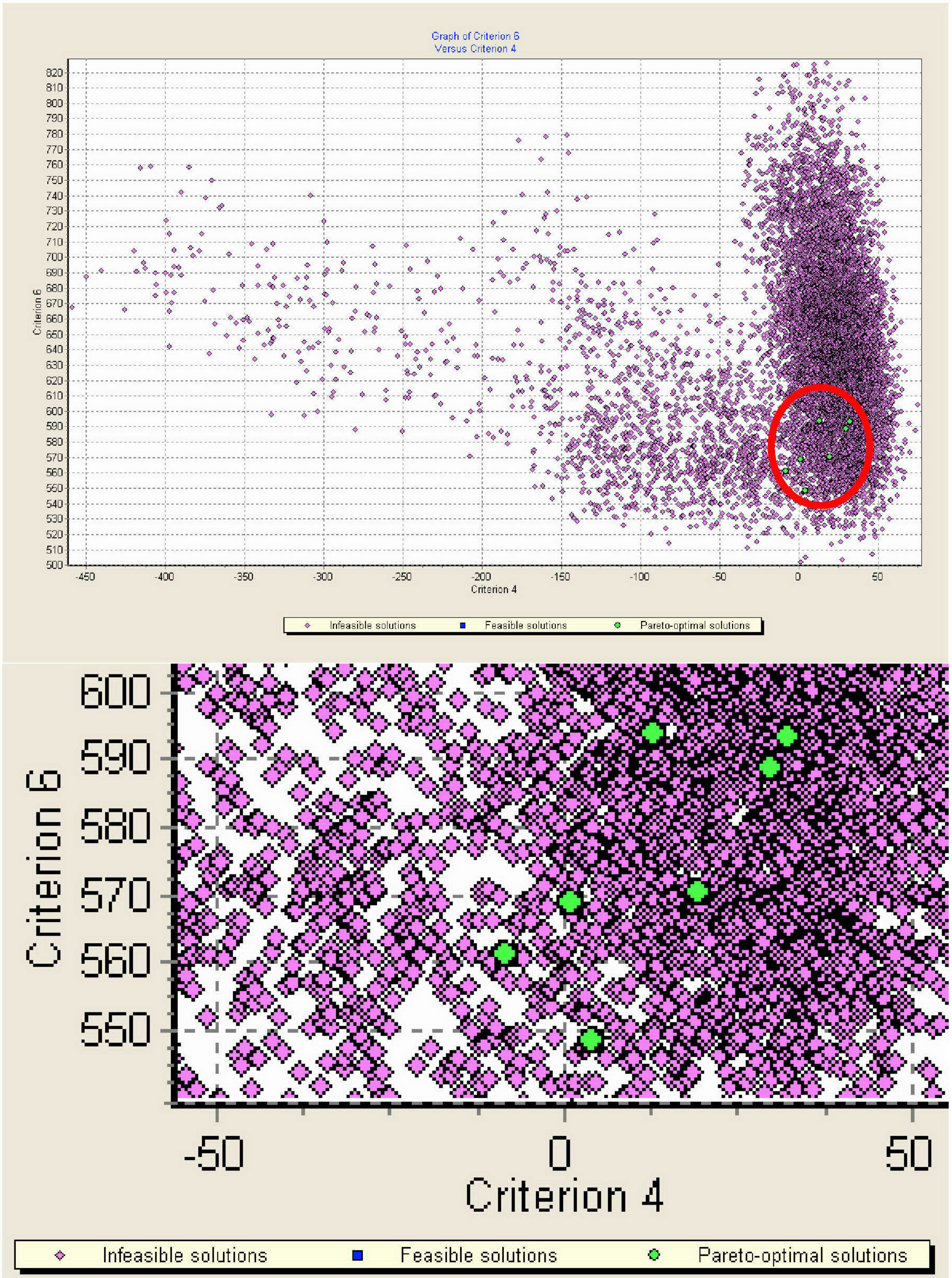

Figure 71 Criterion 4 (Maximized) vs. Criterion 6 (Minimized) – 1st Optimization.

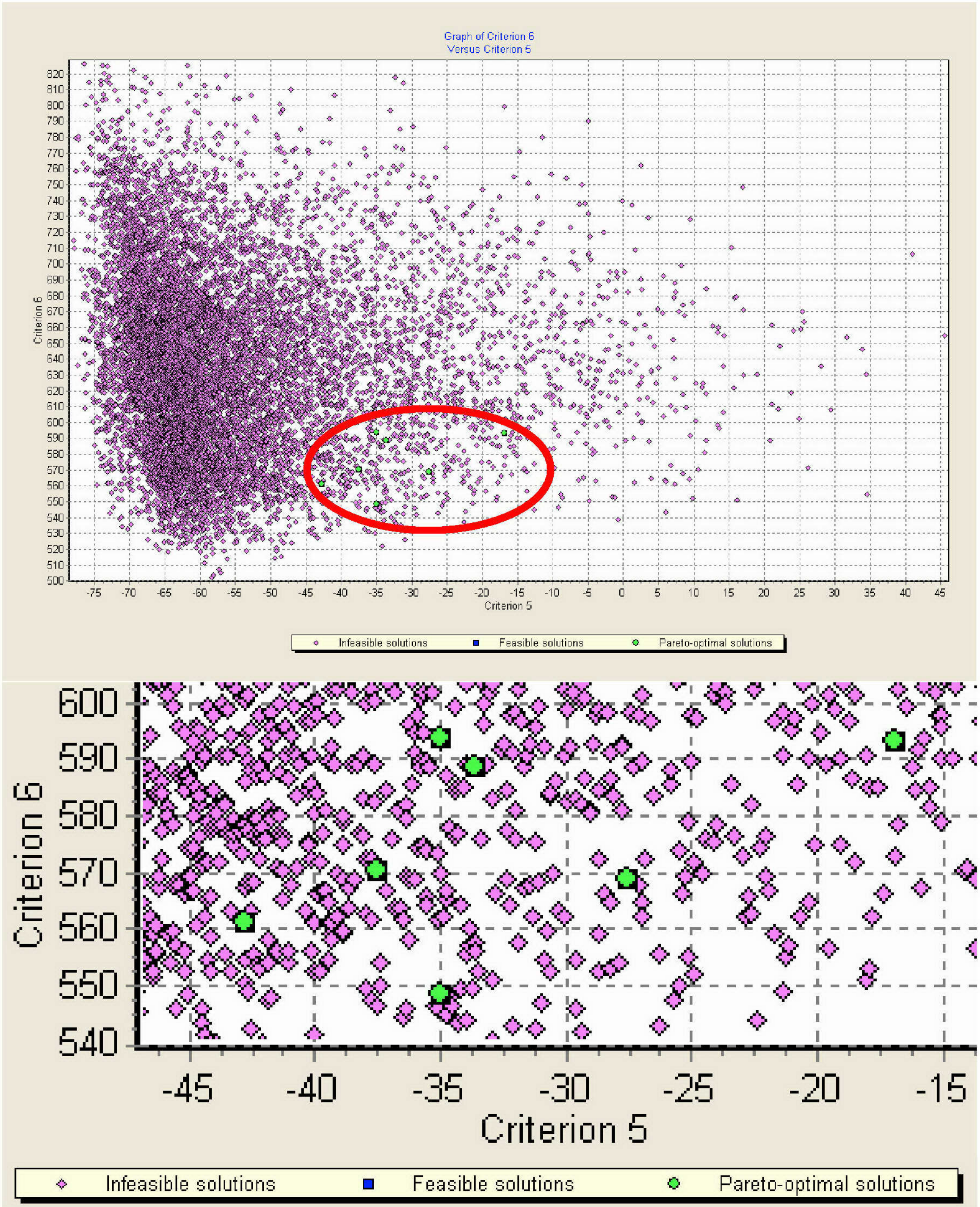

Figure 72 Criterion 5 (Maximized) vs. Criterion 6 (Minimized) – 1st Optimization.

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APPENDIX I. CRITERION VS. CRITERION GRAPHS (MIT MODEL) – 2ND OPTIMIZATION

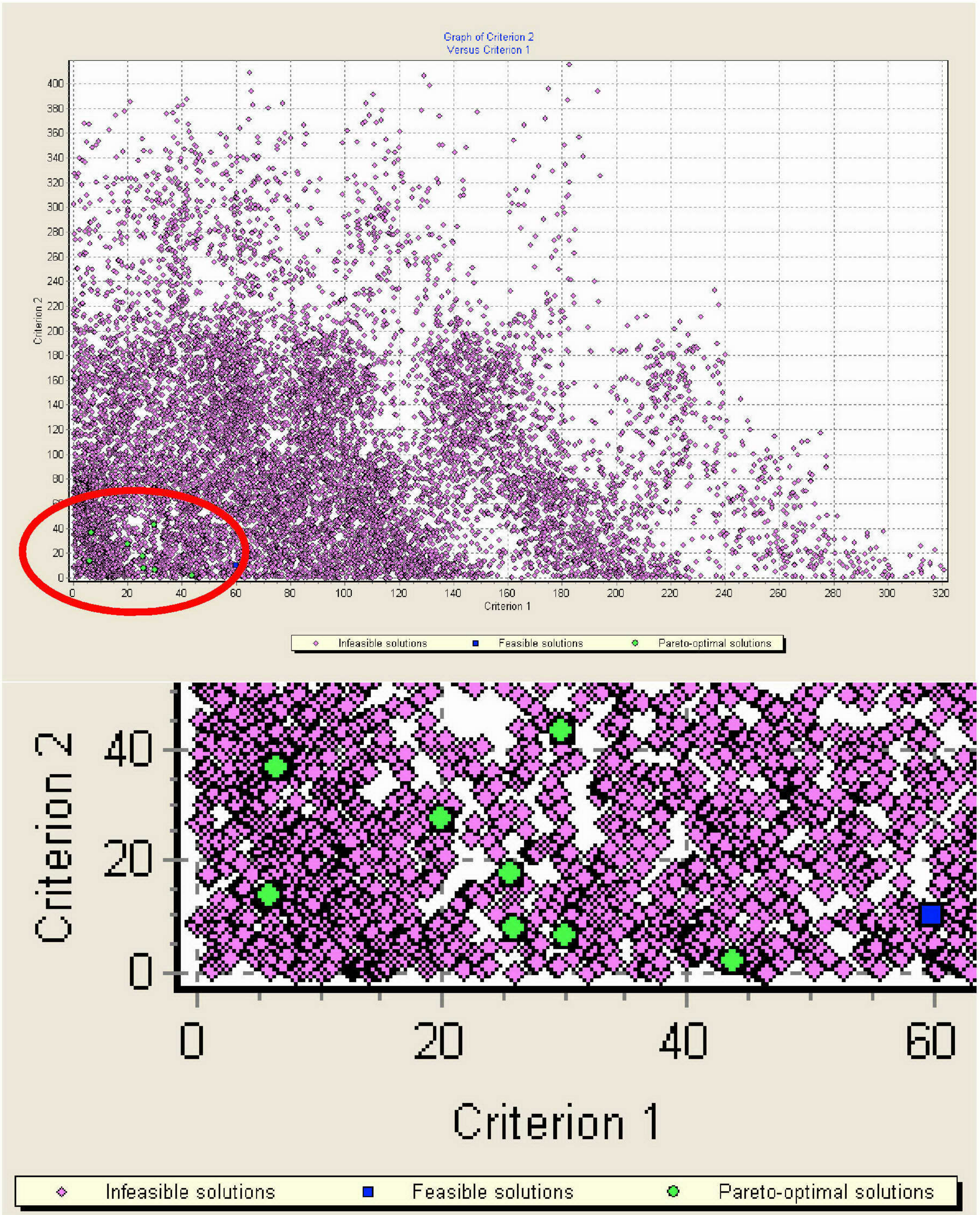

Figure 73 Criterion 1 (Minimized) vs. Criterion 2 (Minimized) – 2nd Optimization.

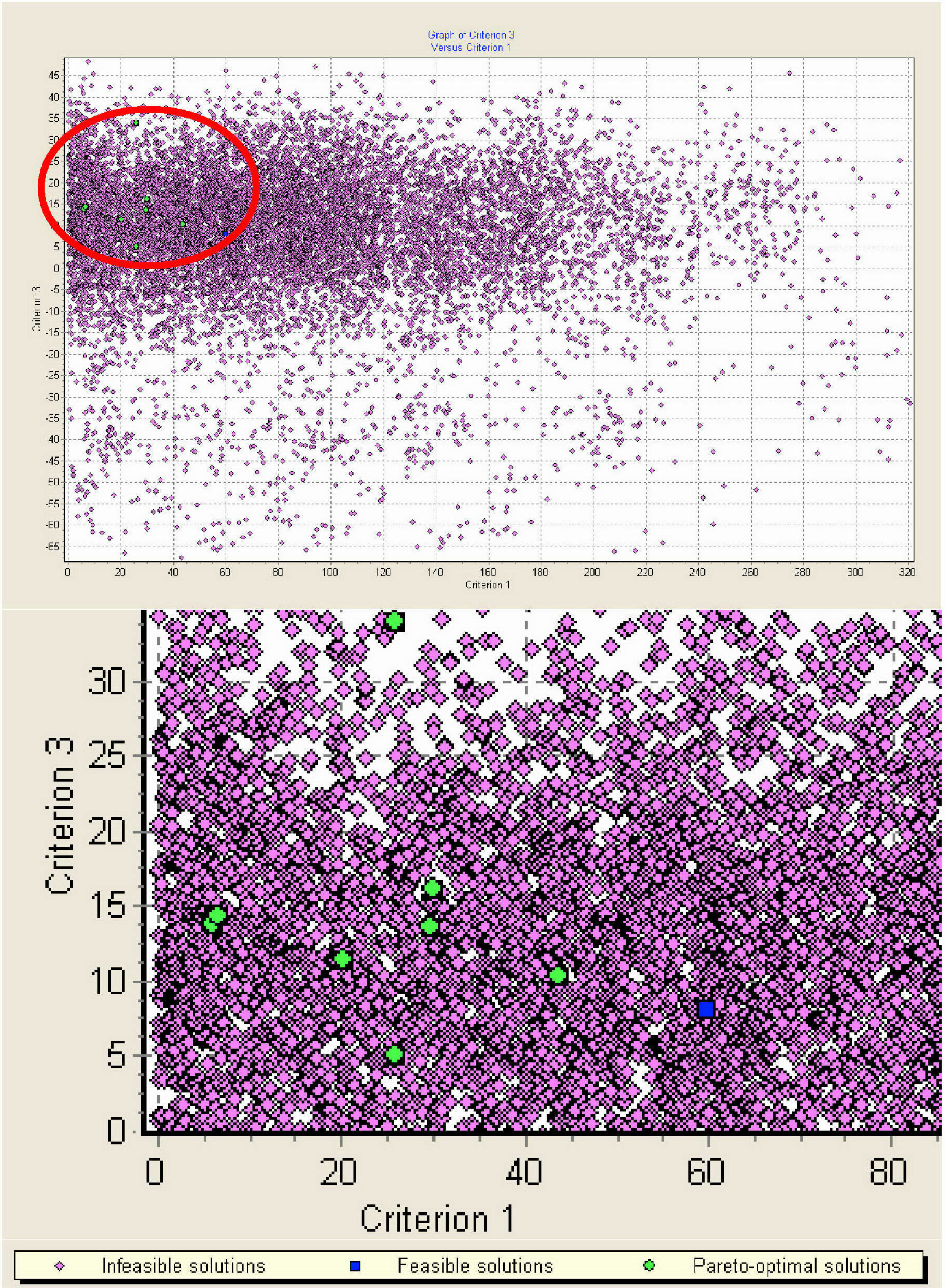

Figure 74 Criterion 1 (Minimized) vs. Criterion 3 (Maximized) – 2nd Optimization.

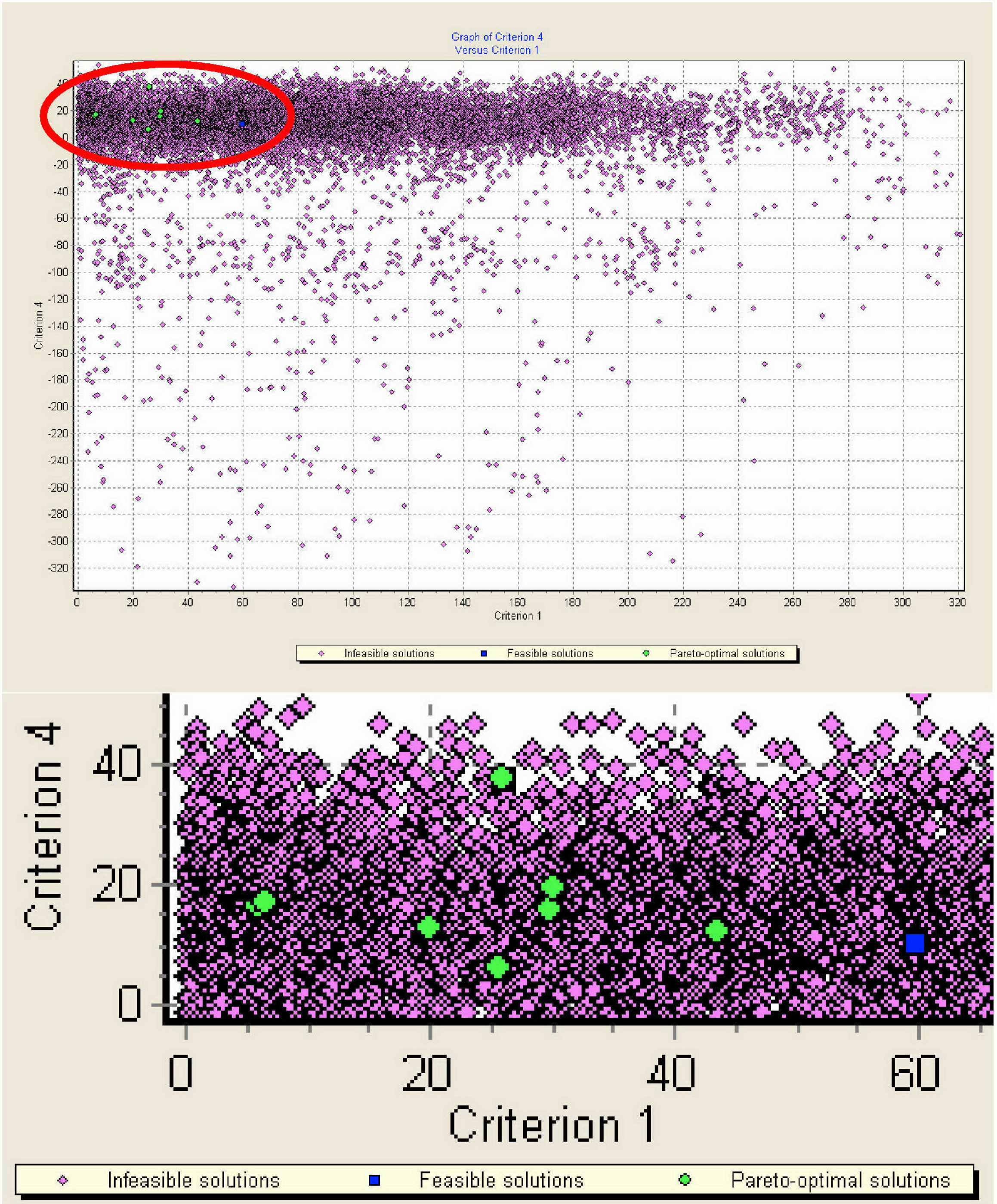

Figure 75 Criterion 1 (Minimized) vs. Criterion 4 (Maximized) – 2nd Optimization.

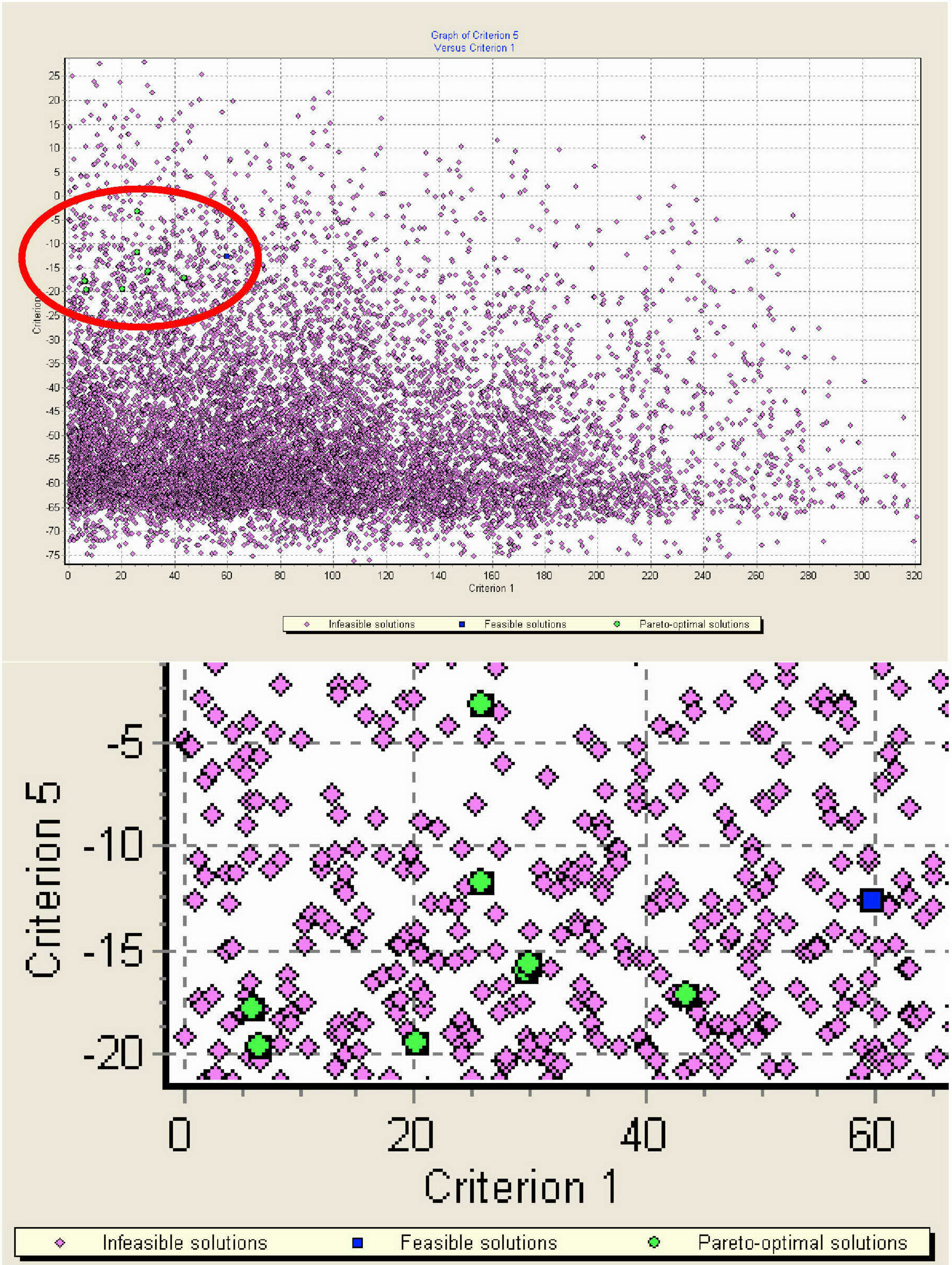

Figure 76 Criterion 1 (Minimized) vs. Criterion 5 (Maximized) – 2nd Optimization.

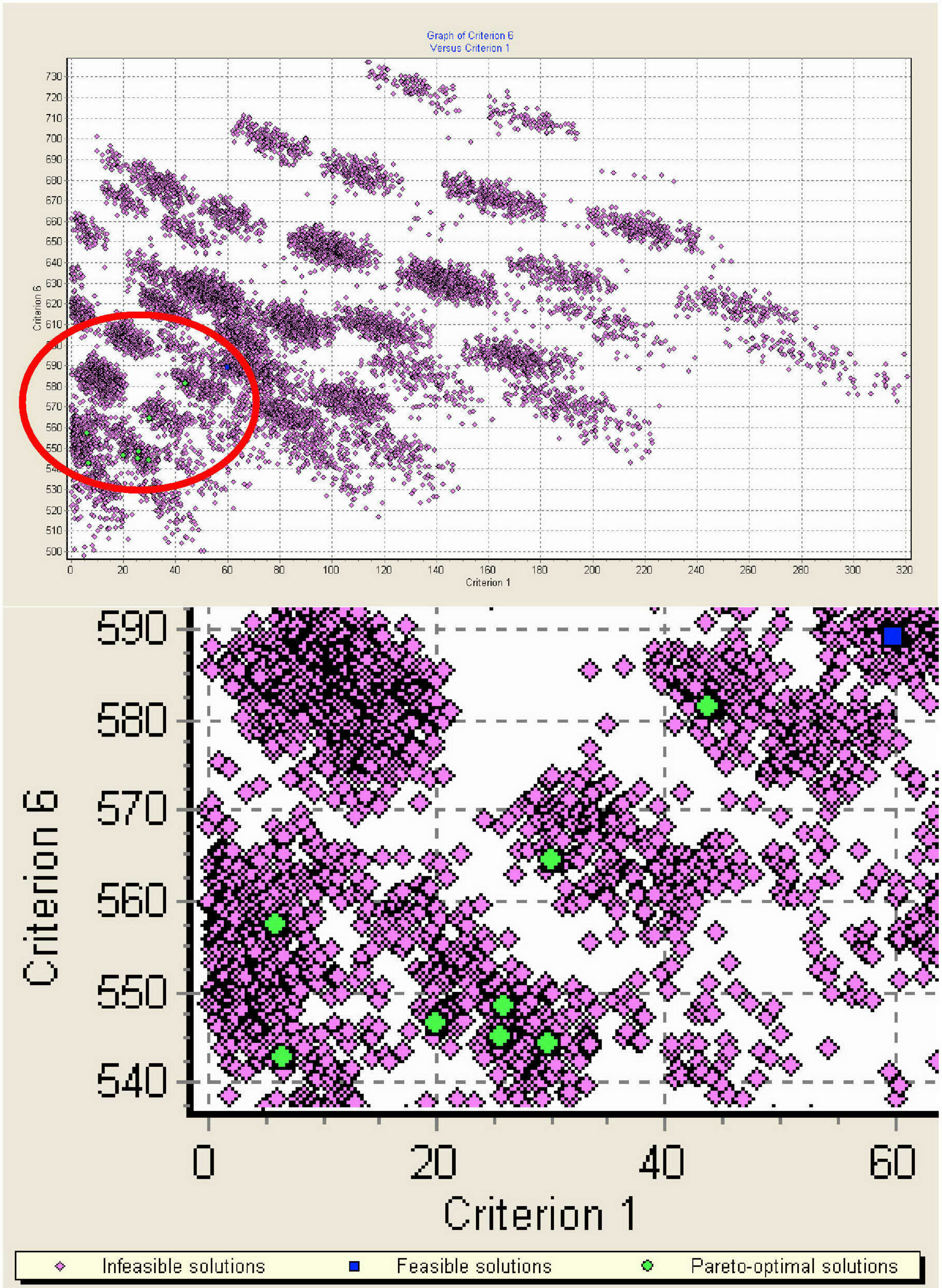

Figure 77 Criterion 1 (Minimized) vs. Criterion 6 (Minimized) – 2nd Optimization.

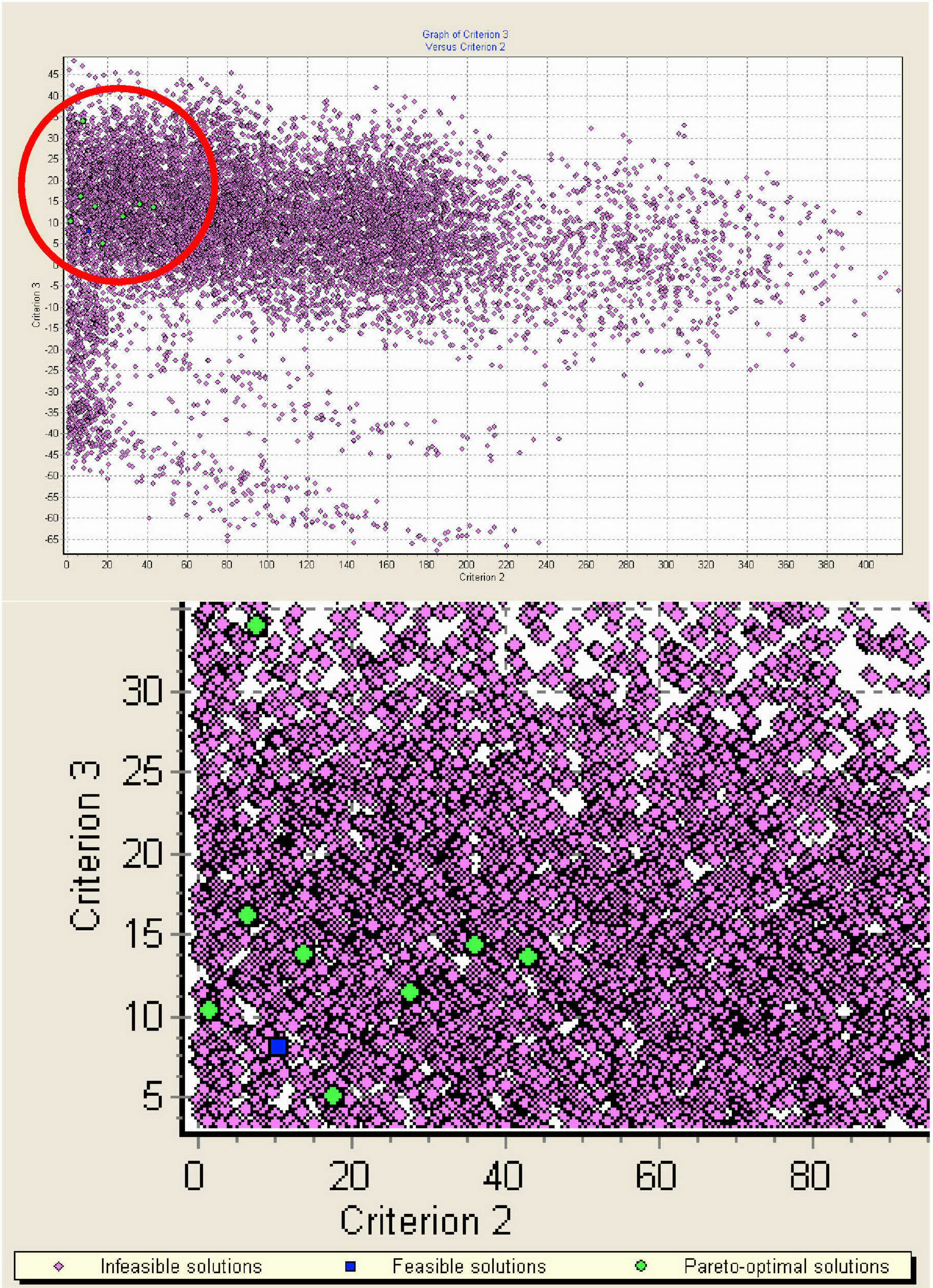

Figure 78 Criterion 2 (Minimized) vs. Criterion 3 (Maximized) – 2nd Optimization.

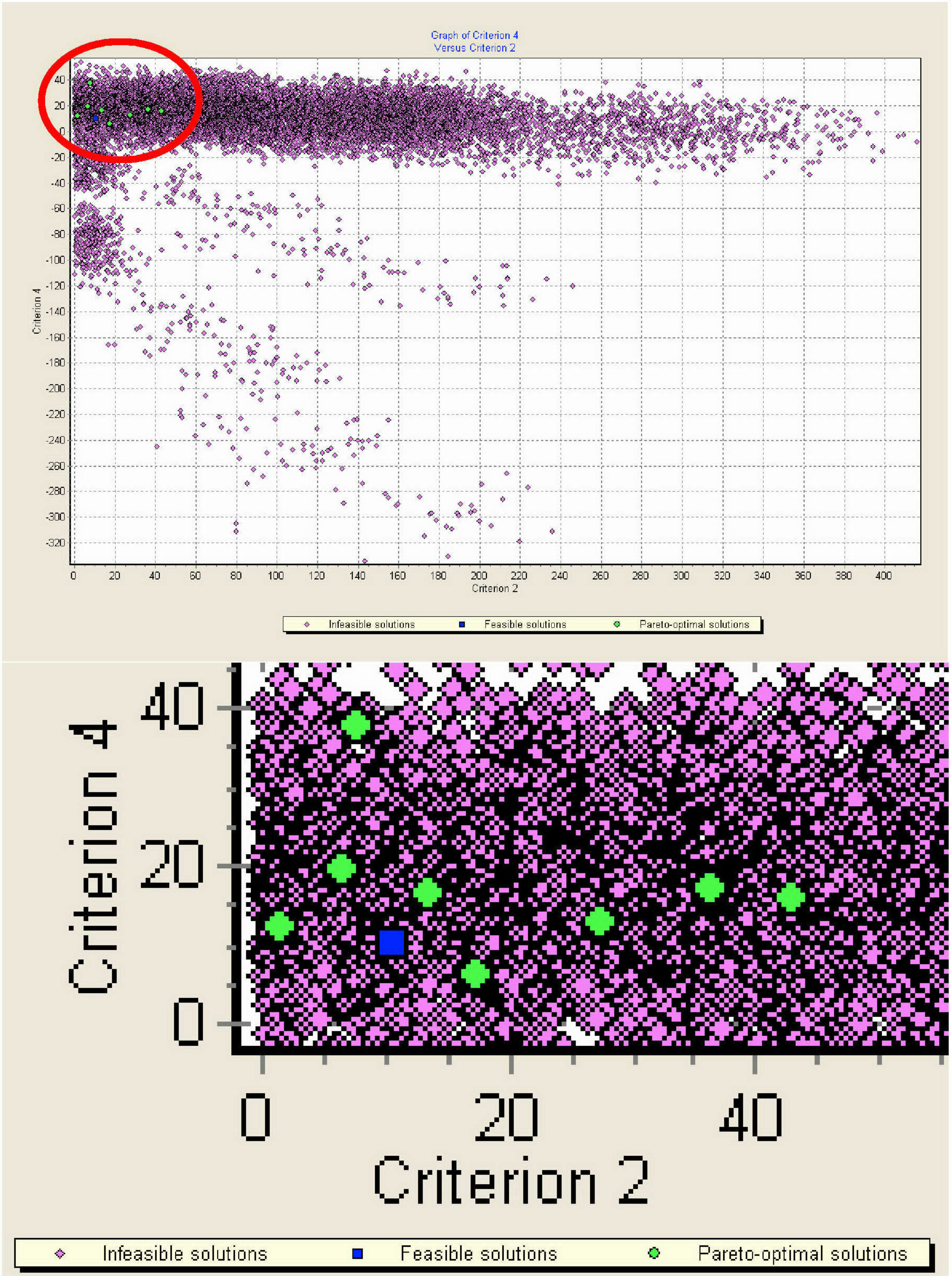

Figure 79 Criterion 2 (Minimized) vs. Criterion 4 (Maximized) – 2nd Optimization.

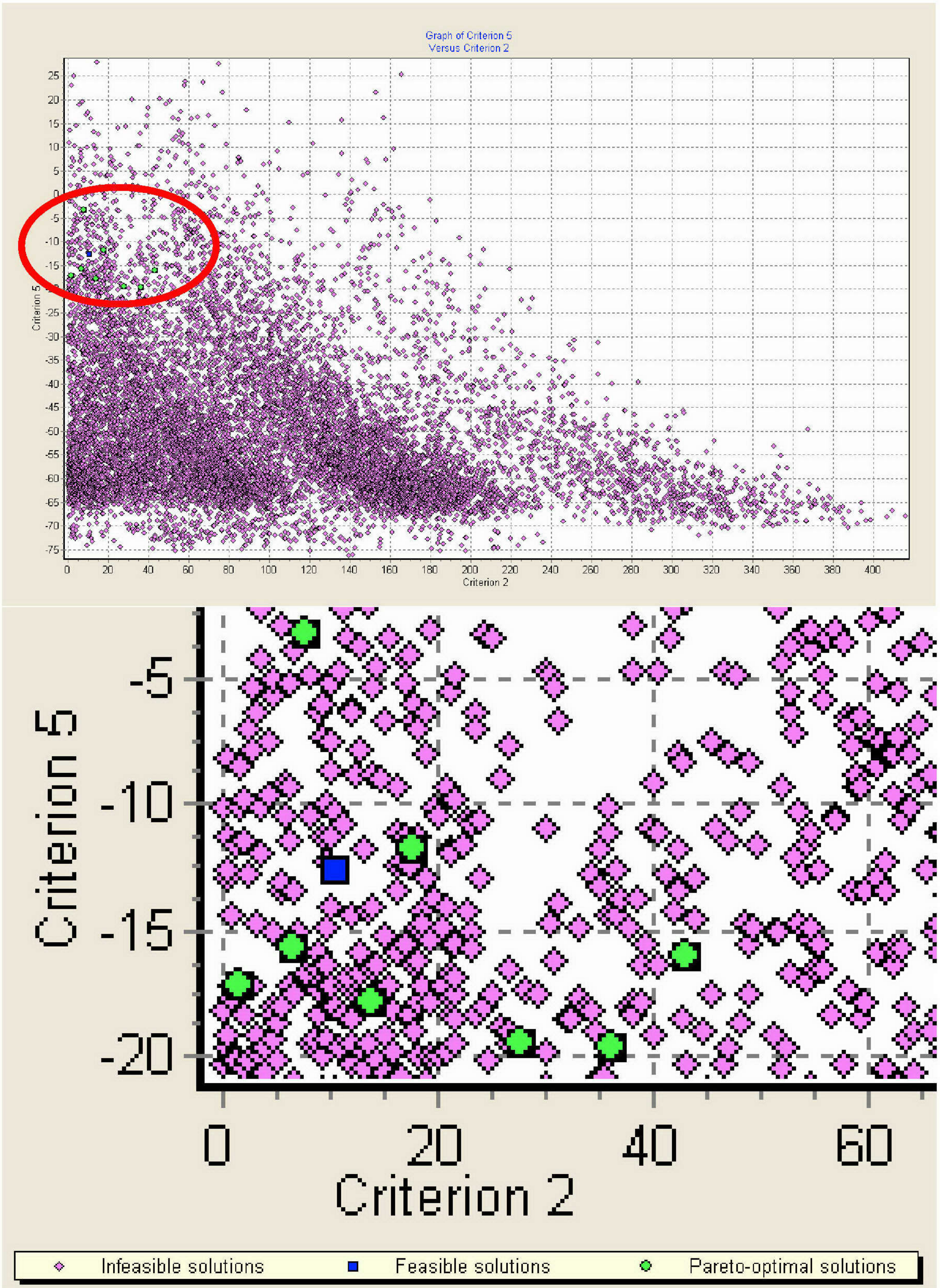

Figure 80 Criterion 2 (Minimized) vs. Criterion 5 (Maximized) – 2^{nd} Optimization.

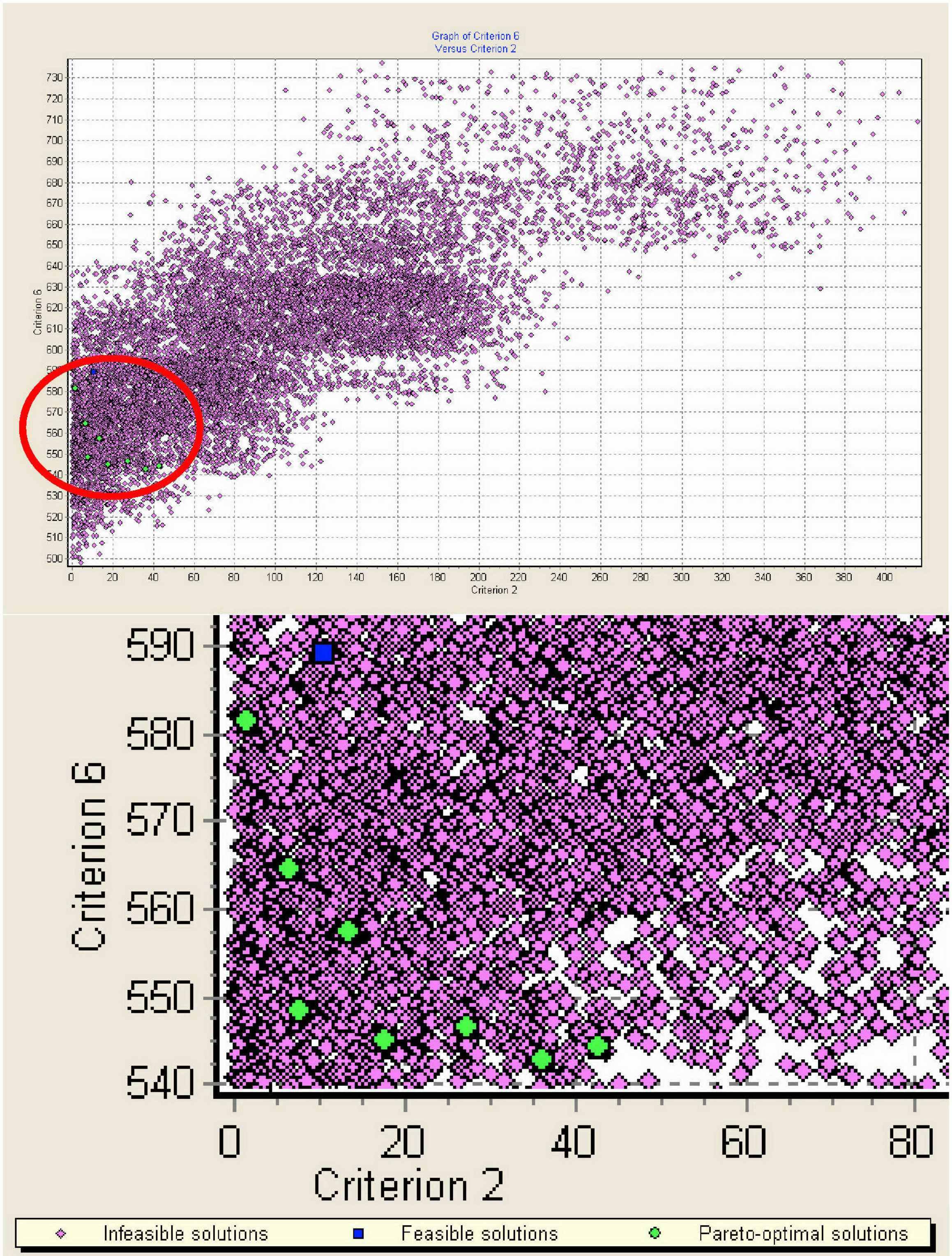

Figure 81 Criterion 2 (Minimized) vs. Criterion 6 (Minimized) – 2nd Optimization.

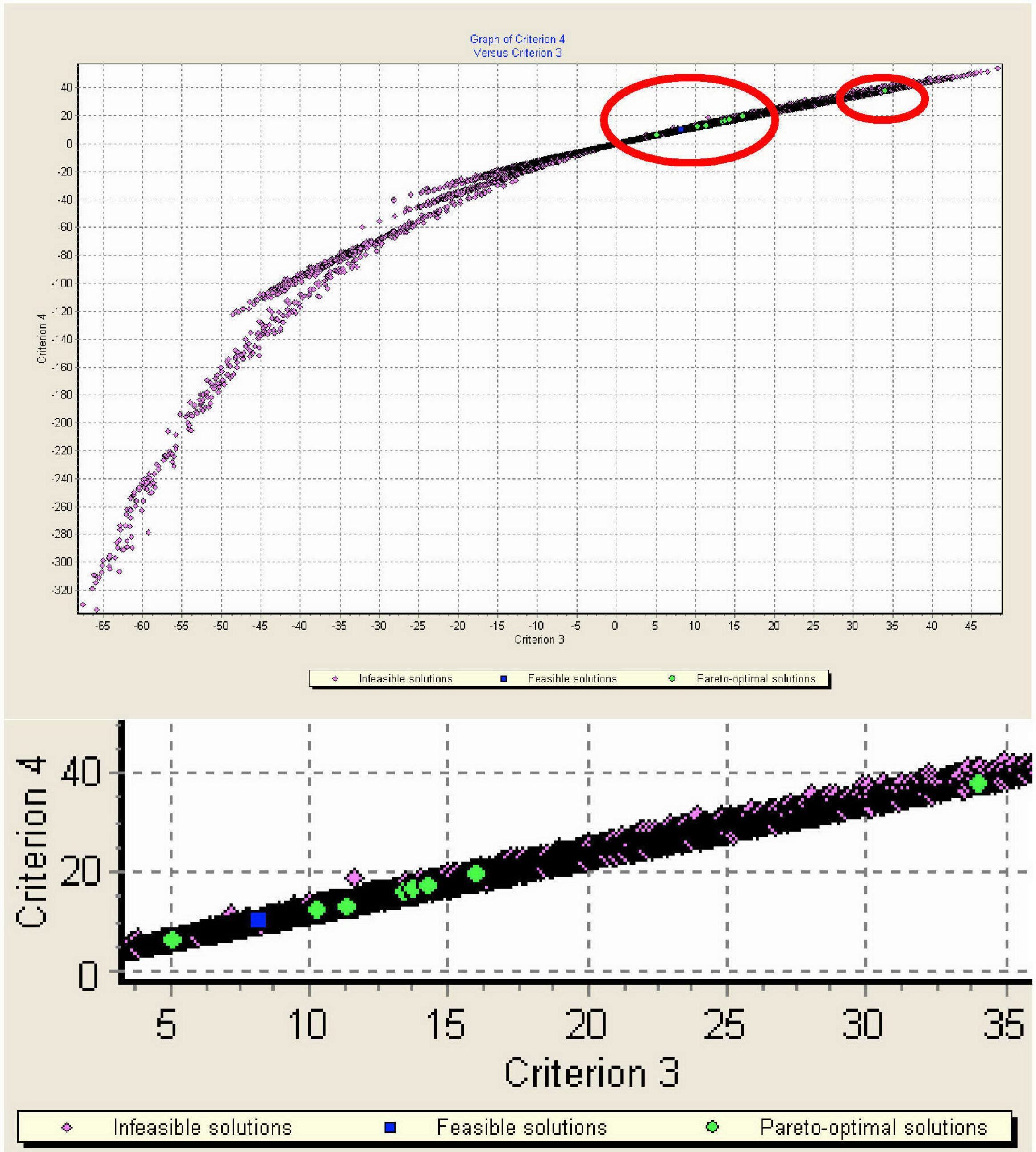

Figure 82 Criterion 3 (Maximized) vs. Criterion 4 (Maximized) – 2nd Optimization.

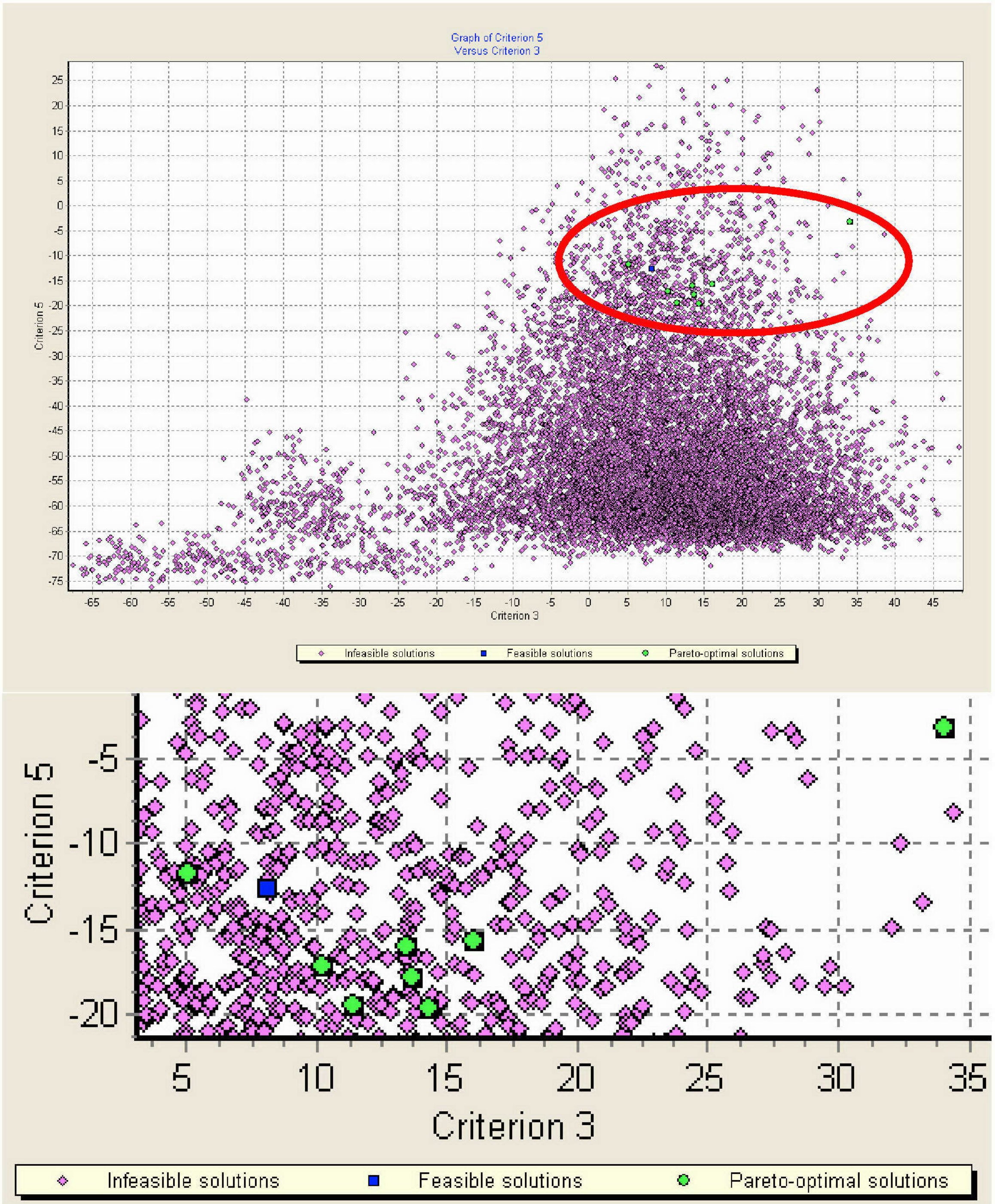

Figure 83 Criterion 3 (Maximized) vs. Criterion 5 (Maximized) – 2nd Optimization.

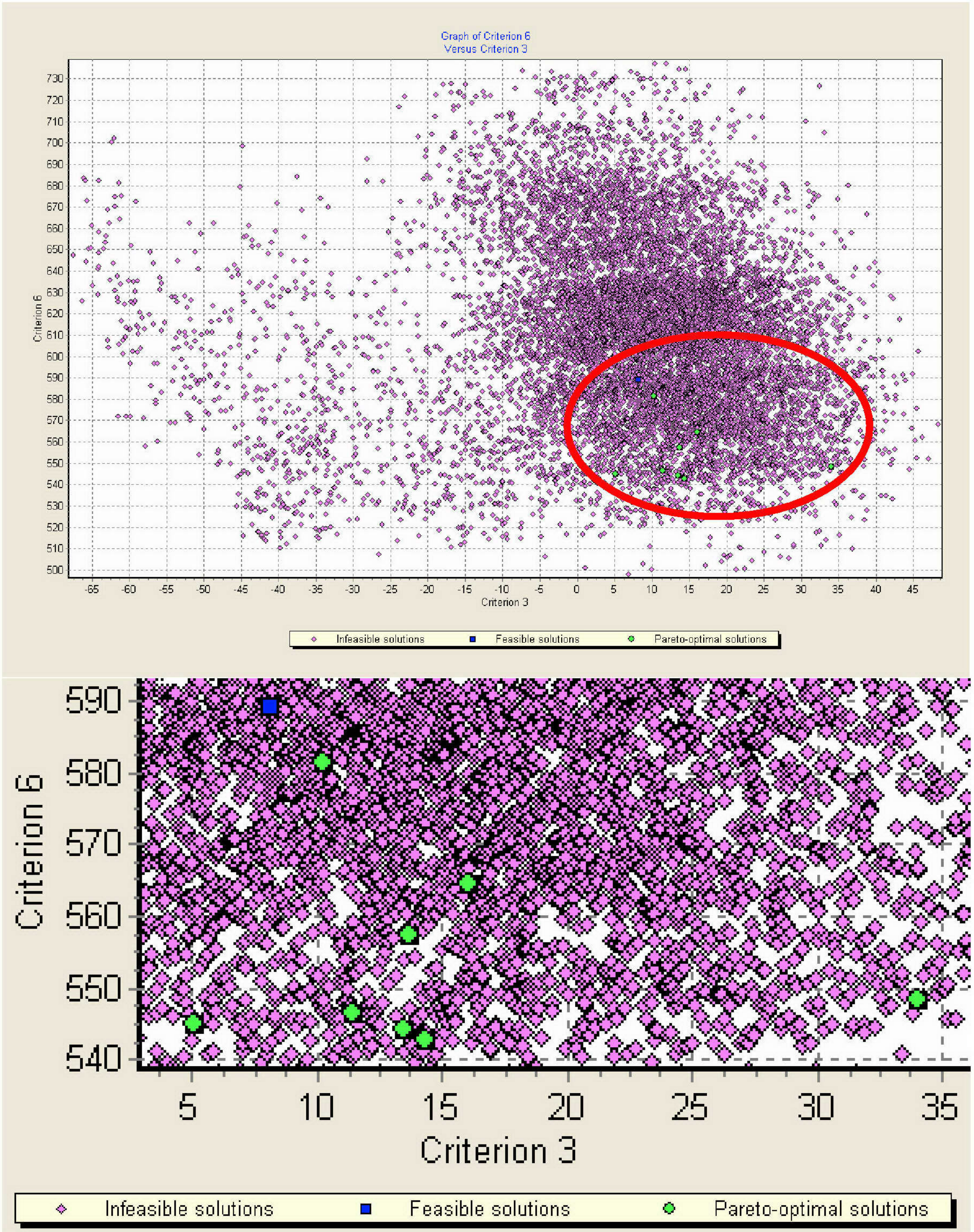

Figure 84 Criterion 3 (Maximized) vs. Criterion 6 (Minimized) – 2nd Optimization.

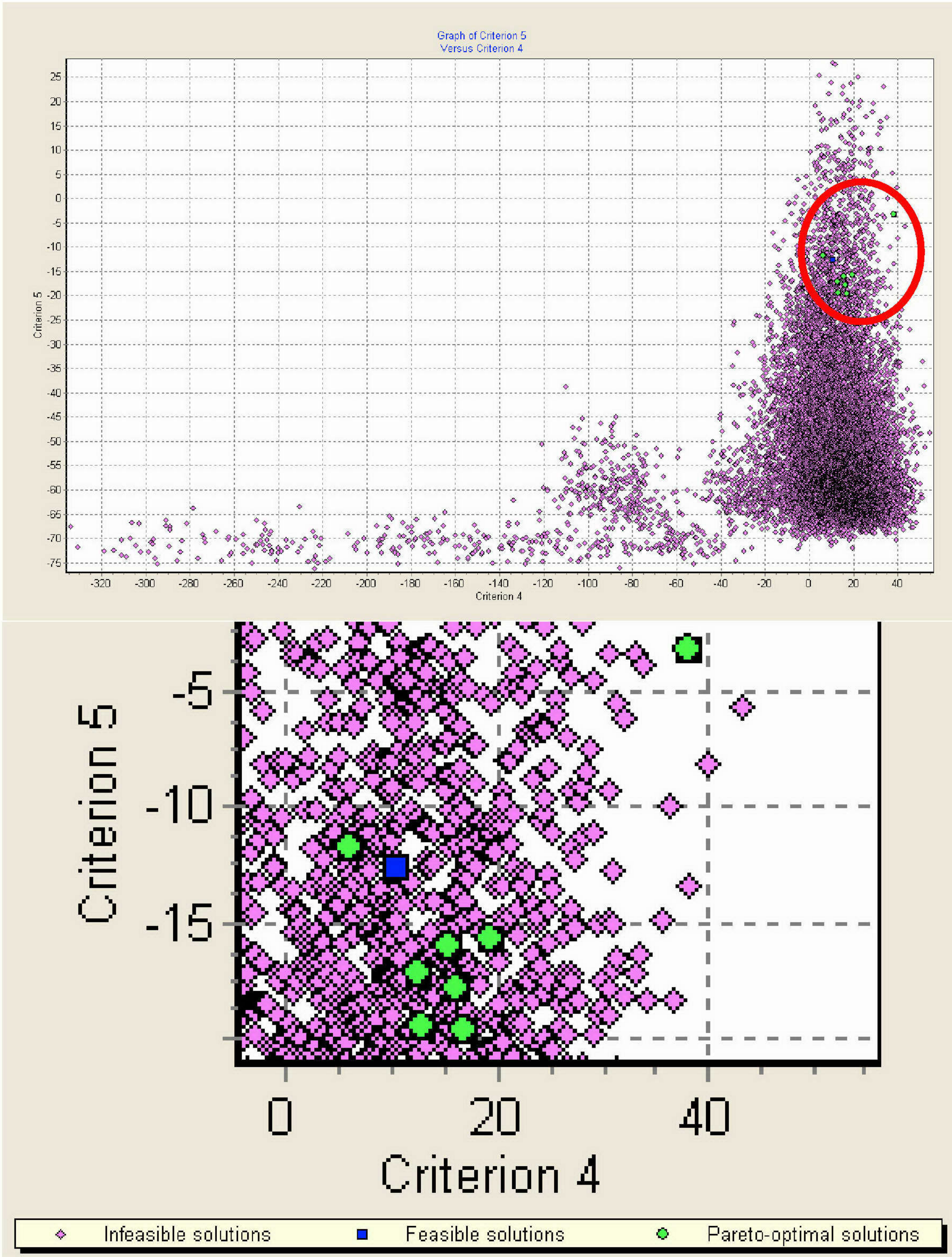

Figure 85 Criterion 4 (Maximized) vs. Criterion 5 (Maximized) – 2nd Optimization.

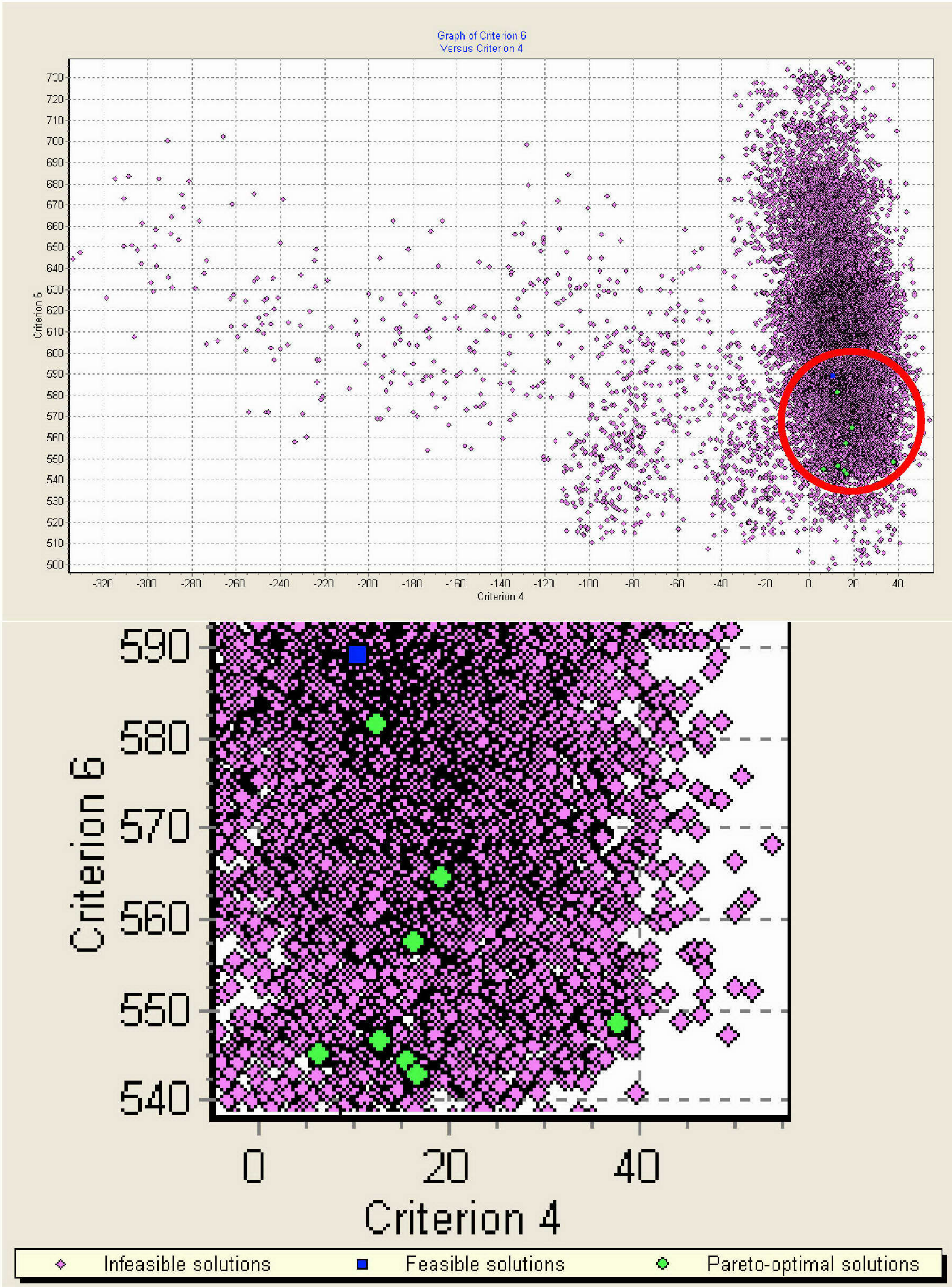

Figure 86 Criterion 4 (Maximized) vs. Criterion 6 (Minimized) – 2nd Optimization.

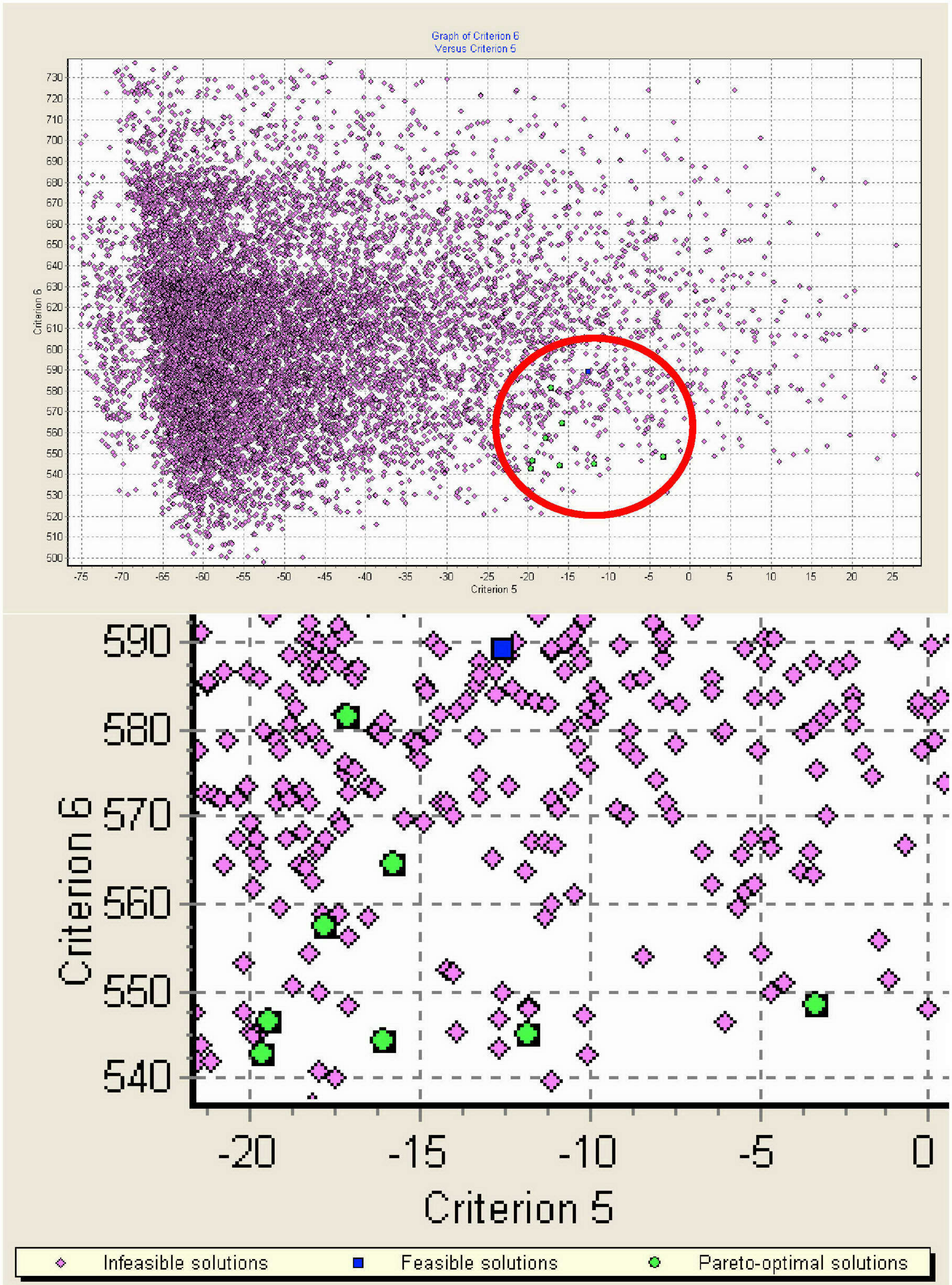

Figure 87 Criterion 5 (Maximized) vs. Criterion 6 (Minimized) – 2nd Optimization.

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APPENDIX J. CRITERION VS. CRITERION GRAPHS (MIT MODEL) – 3RD OPTIMIZATION

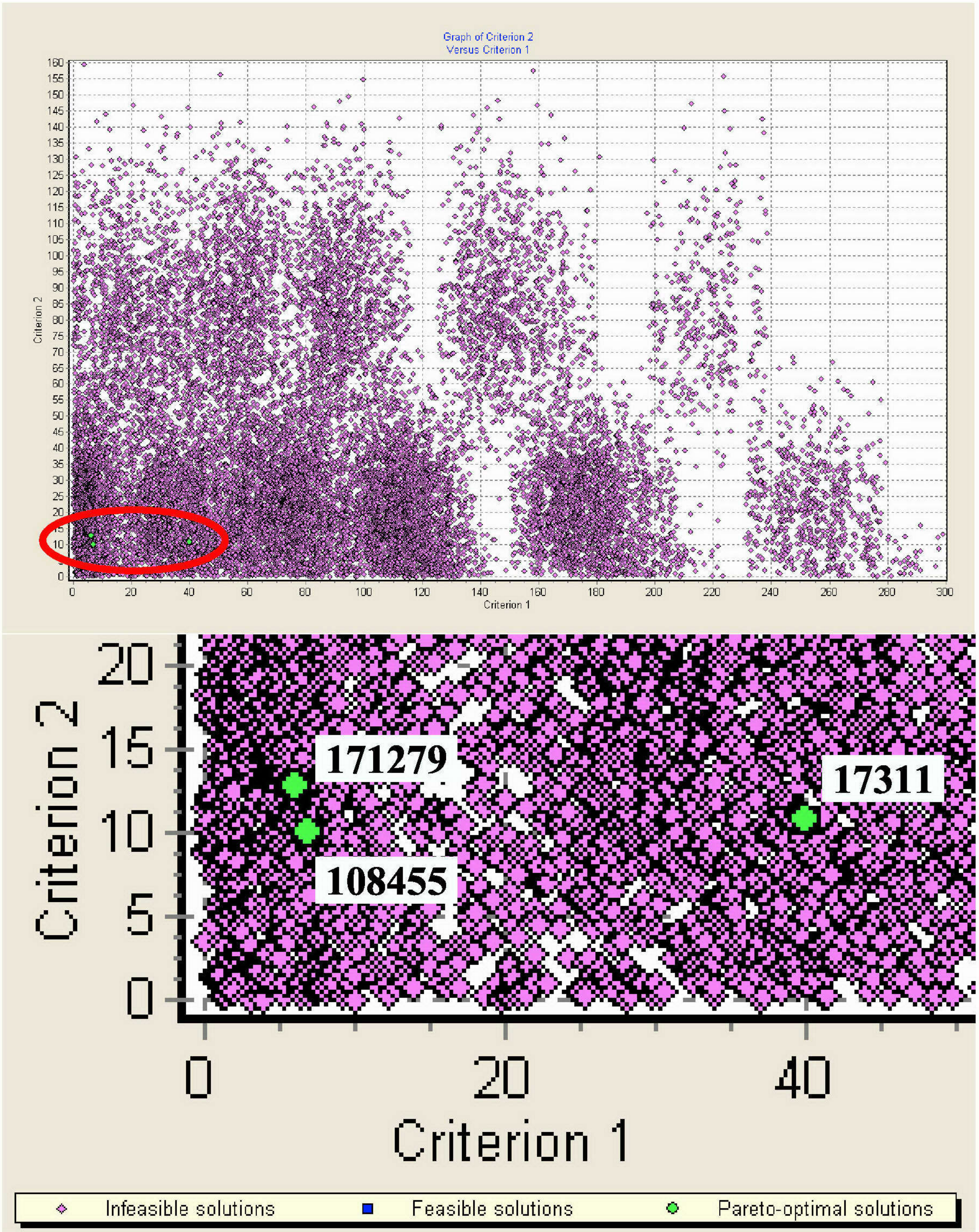

Figure 88 Criterion 1 (Minimized) vs. Criterion 2 (Minimized) – 3rd Optimization.

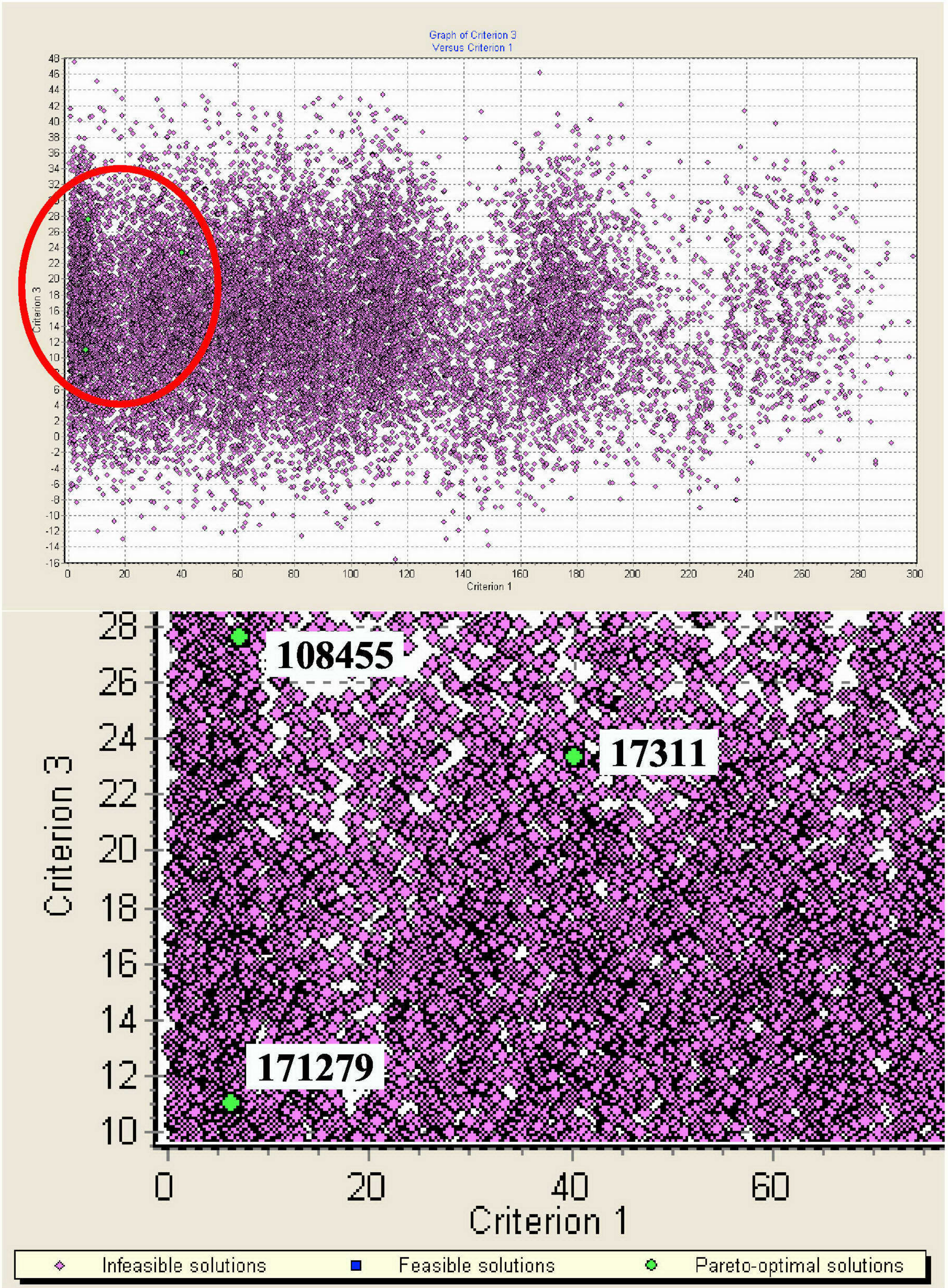

Figure 89 Criterion 1 (Minimized) vs. Criterion 3 (Maximized) – 3rd Optimization.

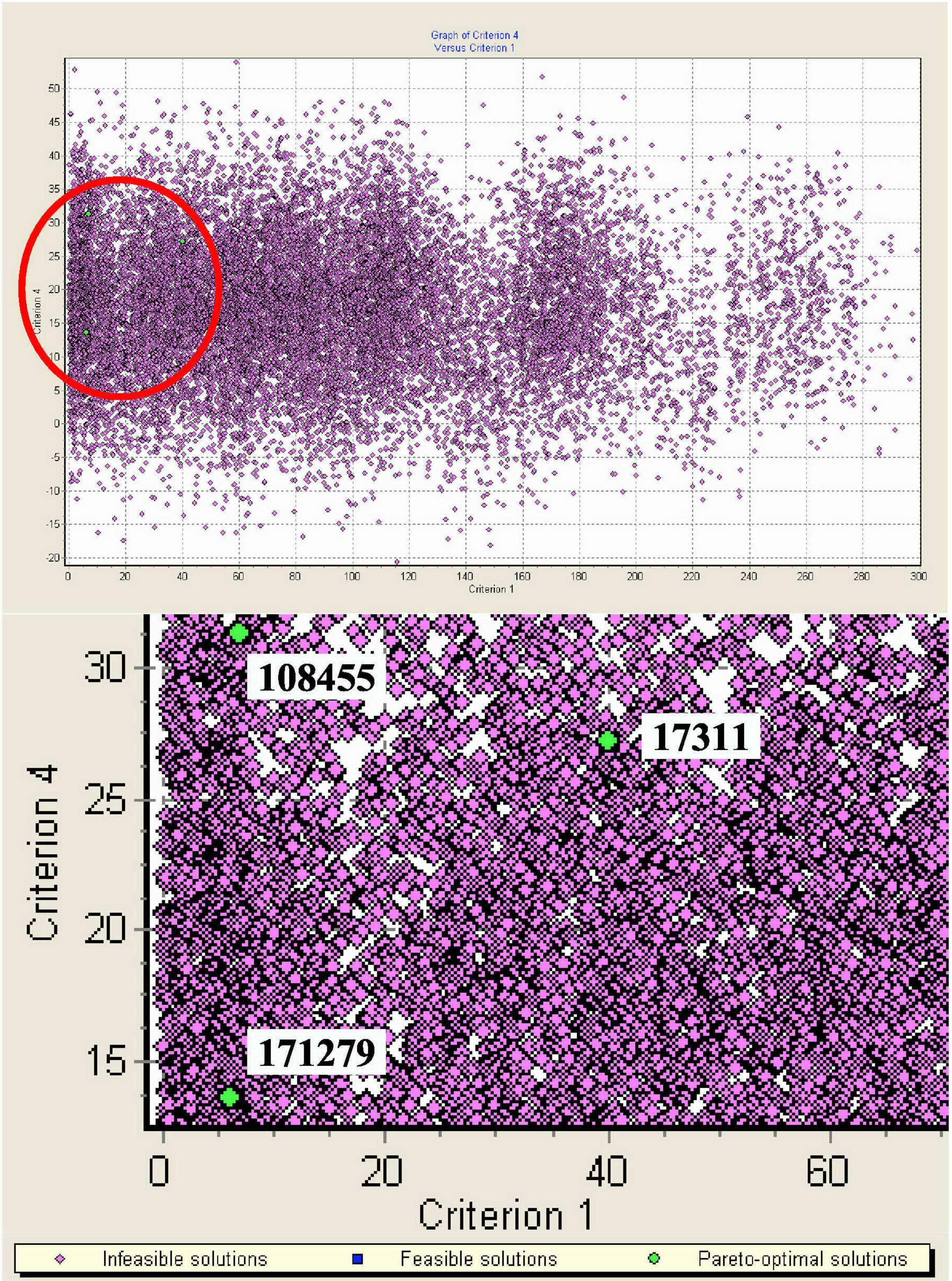

Figure 90 Criterion 1 (Minimized) vs. Criterion 4 (Maximized) – 3rd Optimization.

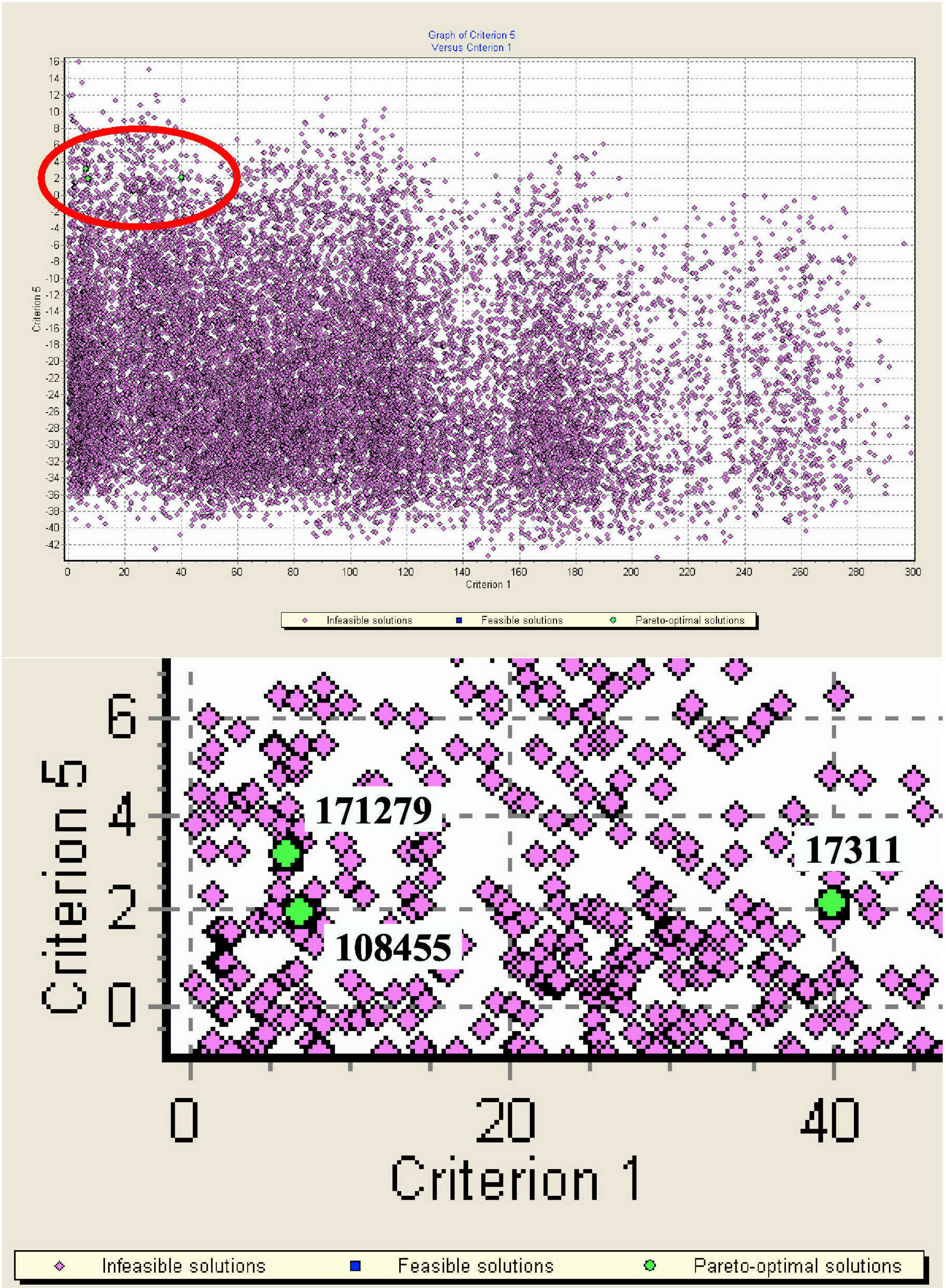

Figure 91 Criterion 1 (Minimized) vs. Criterion 5 (Maximized) – 3rd Optimization.

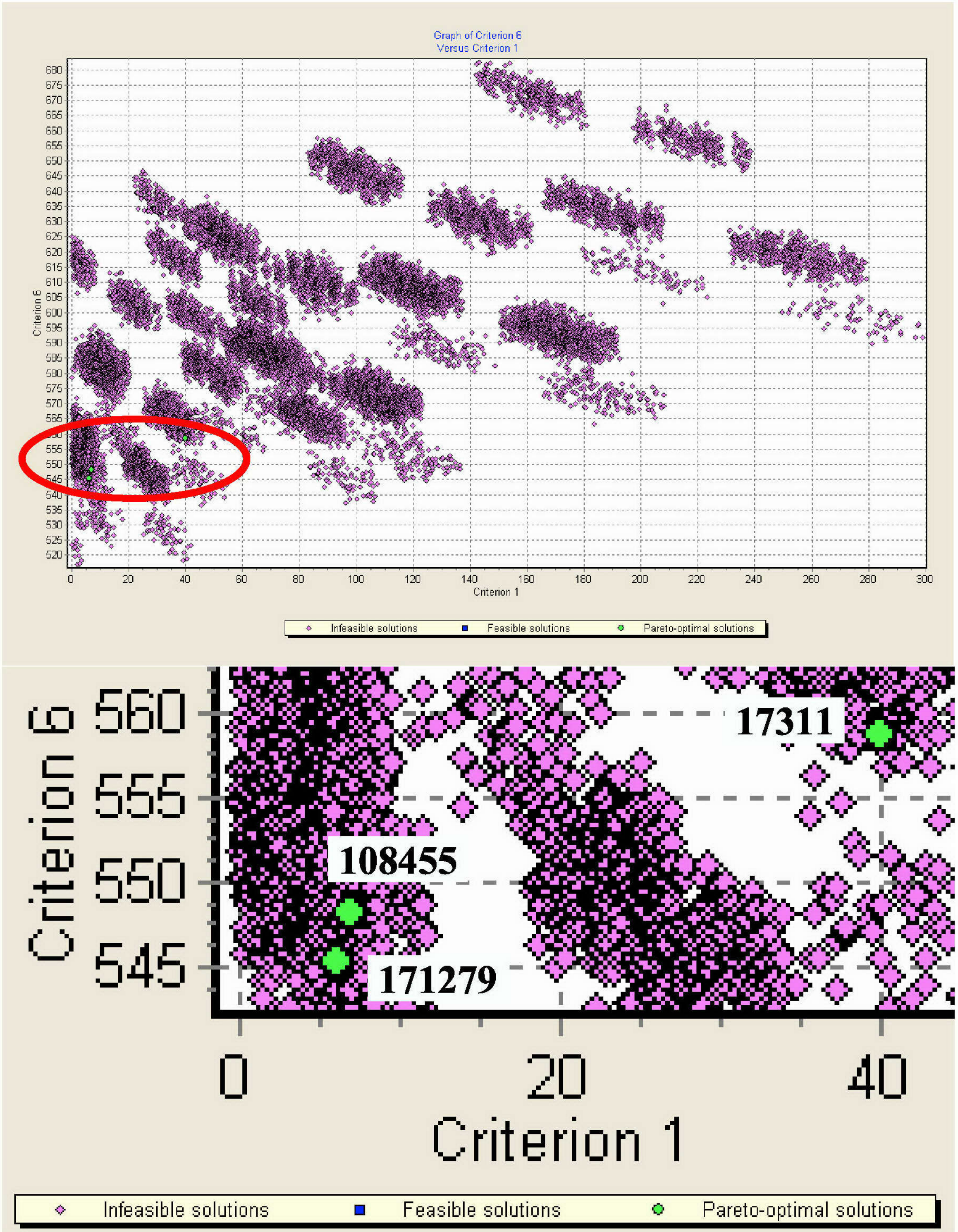

Figure 92 Criterion 1 (Minimized) vs. Criterion 6 (Minimized) – 3rd Optimization.

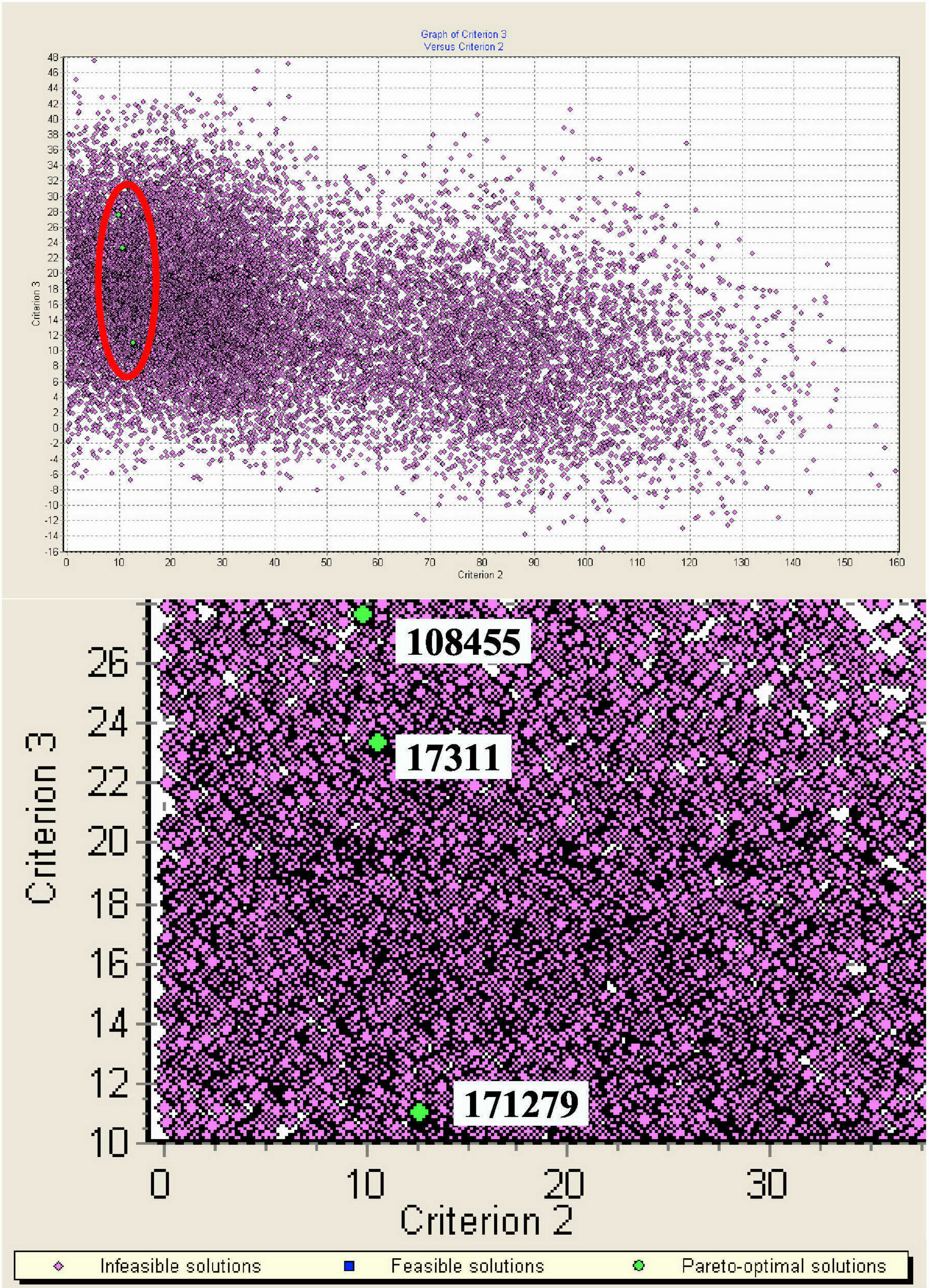

Figure 93 Criterion 2 (Minimized) vs. Criterion 3 (Maximized) – 3rd Optimization.

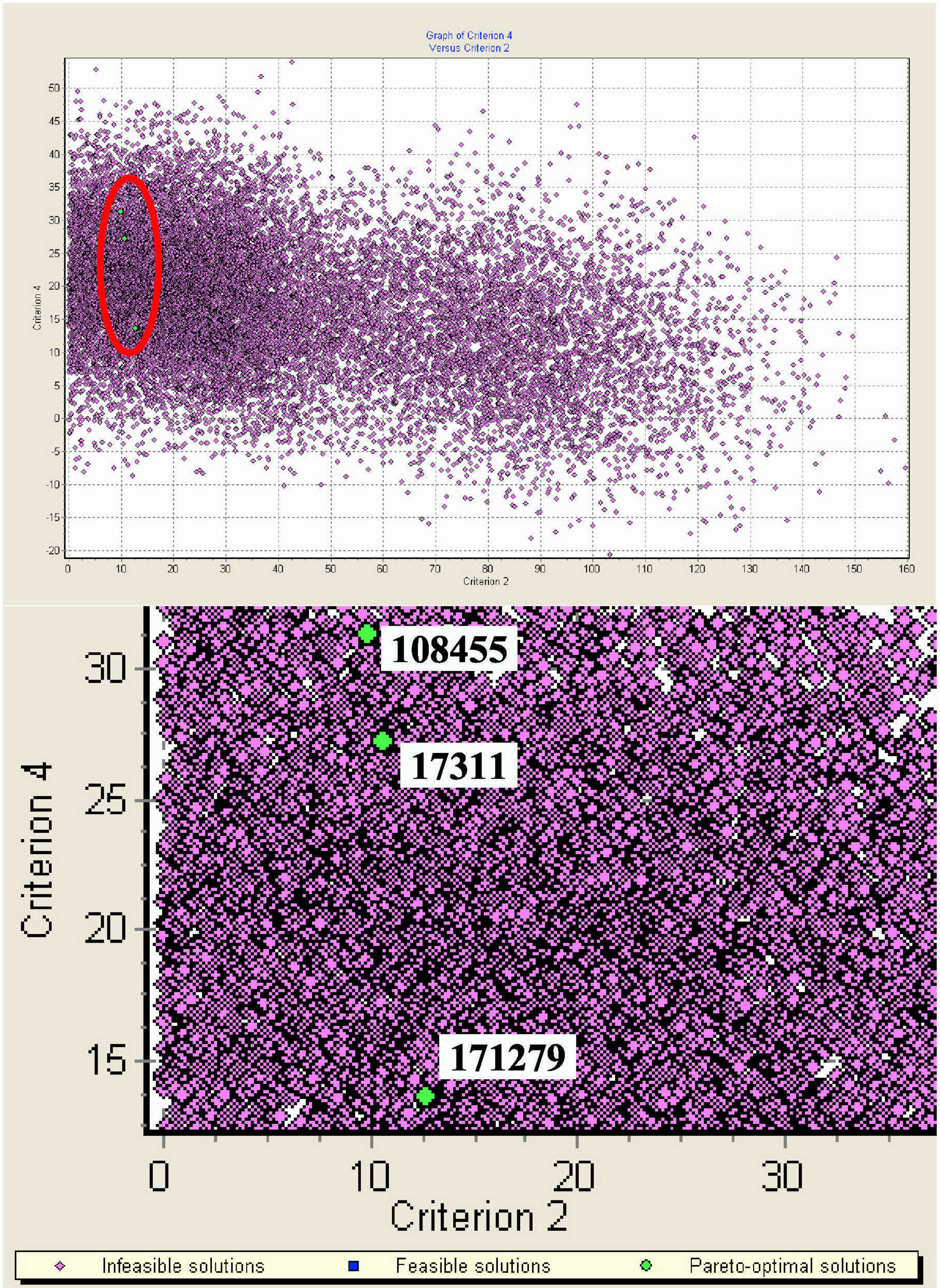

Figure 94 Criterion 2 (Minimized) vs. Criterion 4 (Maximized) – 3rd Optimization.

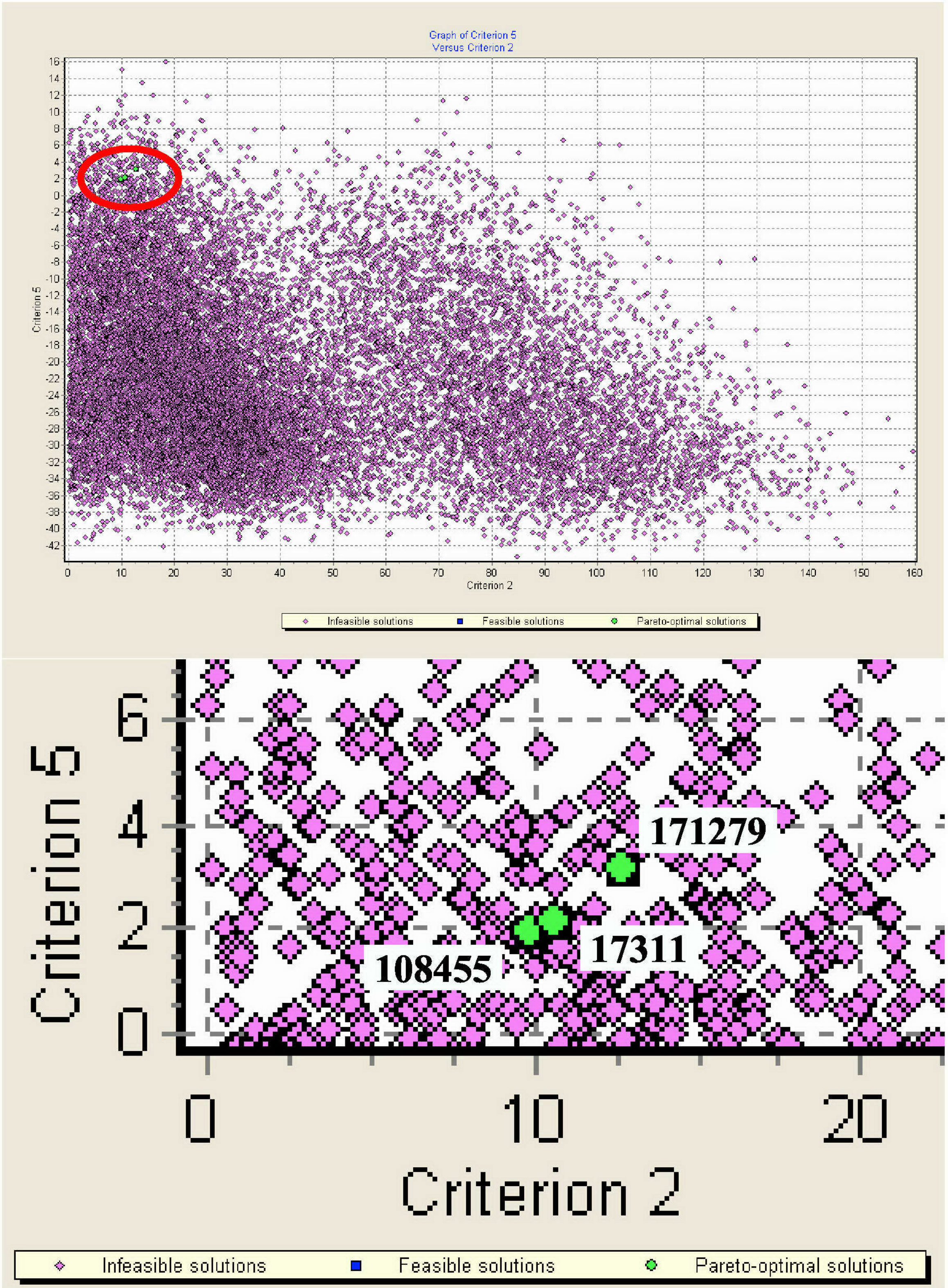

Figure 95 Criterion 2 (Minimized) vs. Criterion 5 (Maximized) – 3rd Optimization.

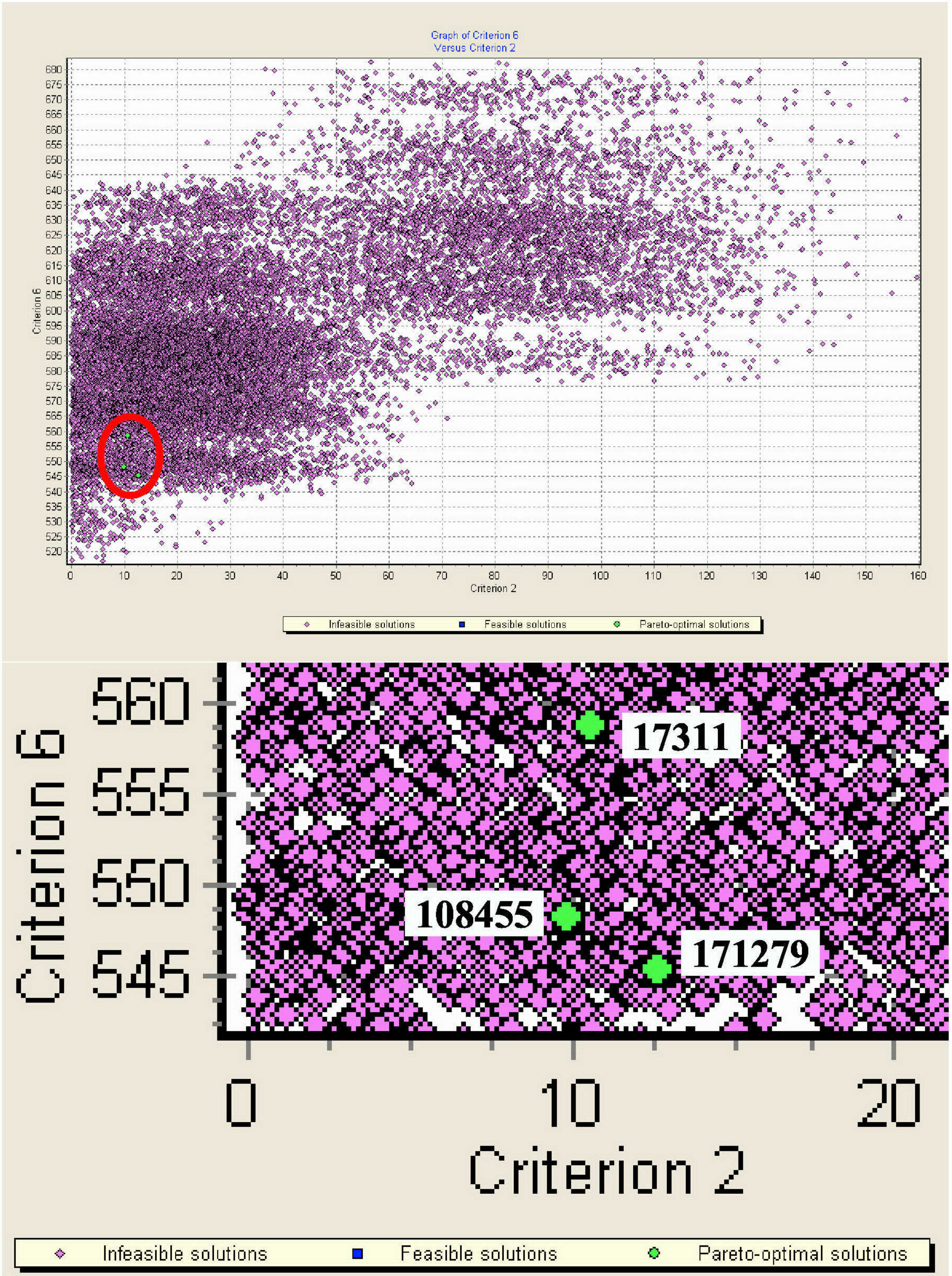

Figure 96 Criterion 2 (Minimized) vs. Criterion 6 (Minimized) – 3rd Optimization.

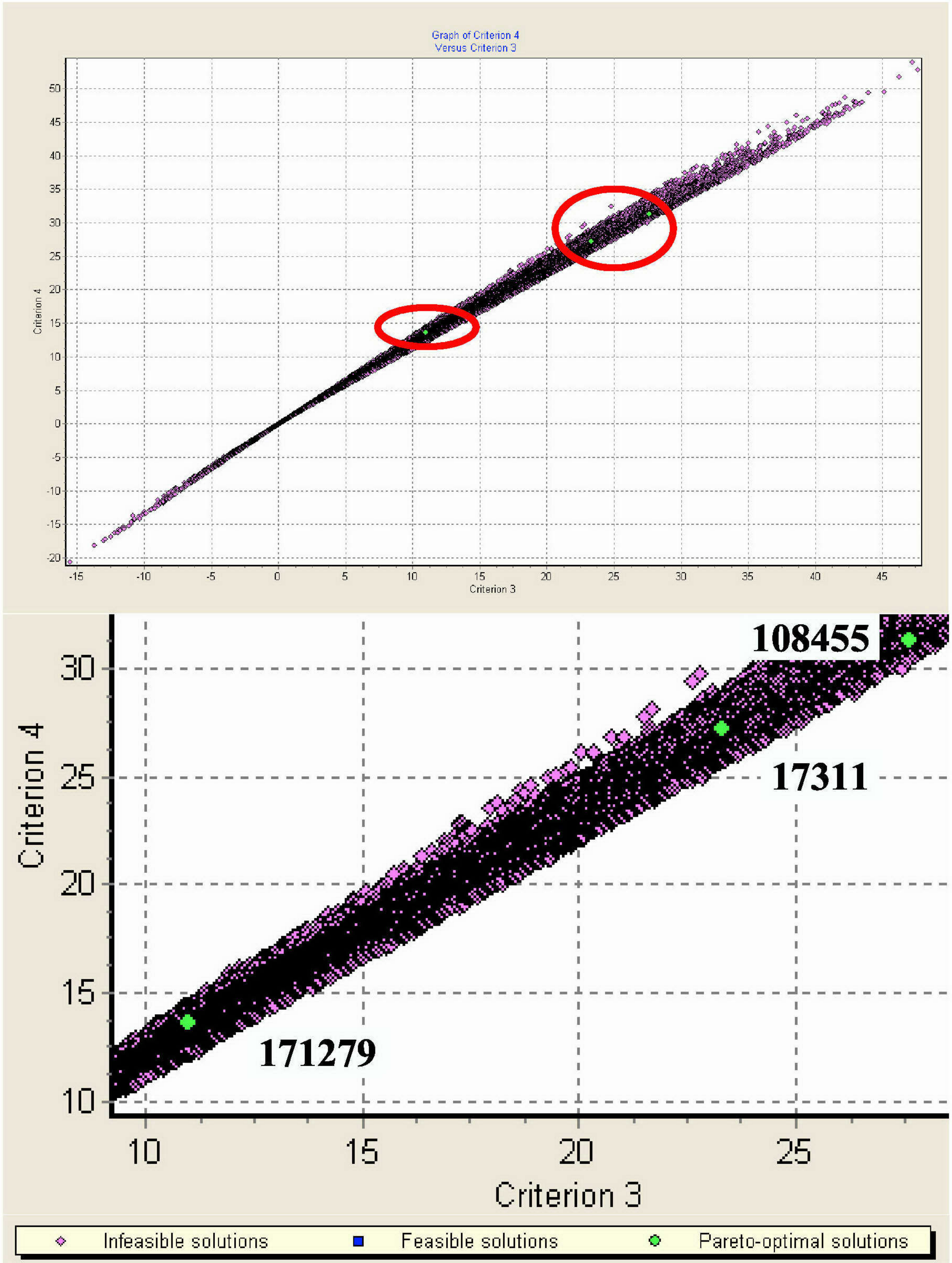

Figure 97 Criterion 3 (Maximized) vs. Criterion 4 (Maximized) – 3rd Optimization.

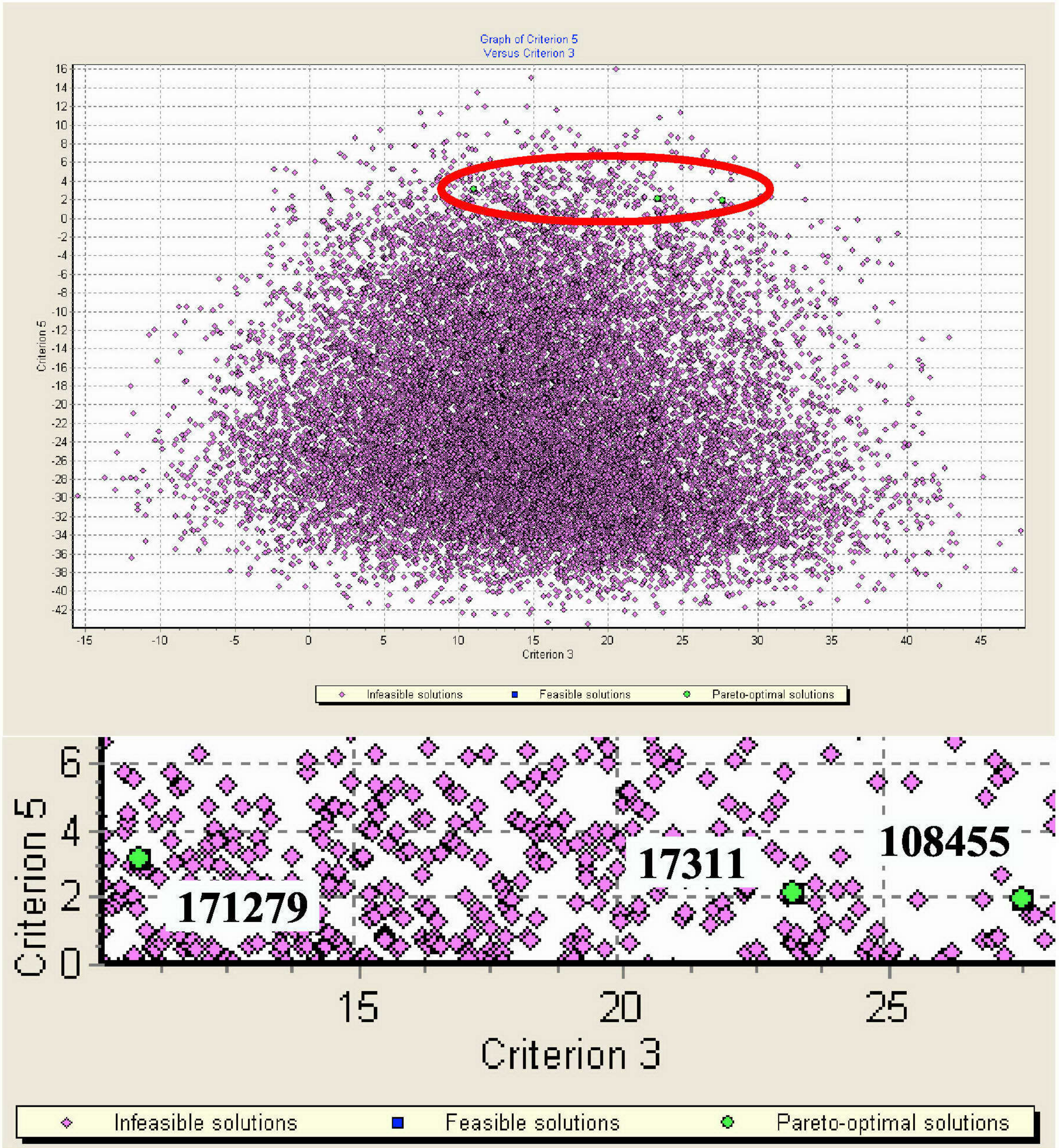

Figure 98 Criterion 3 (Maximized) vs. Criterion 5 (Maximized) – 3rd Optimization.

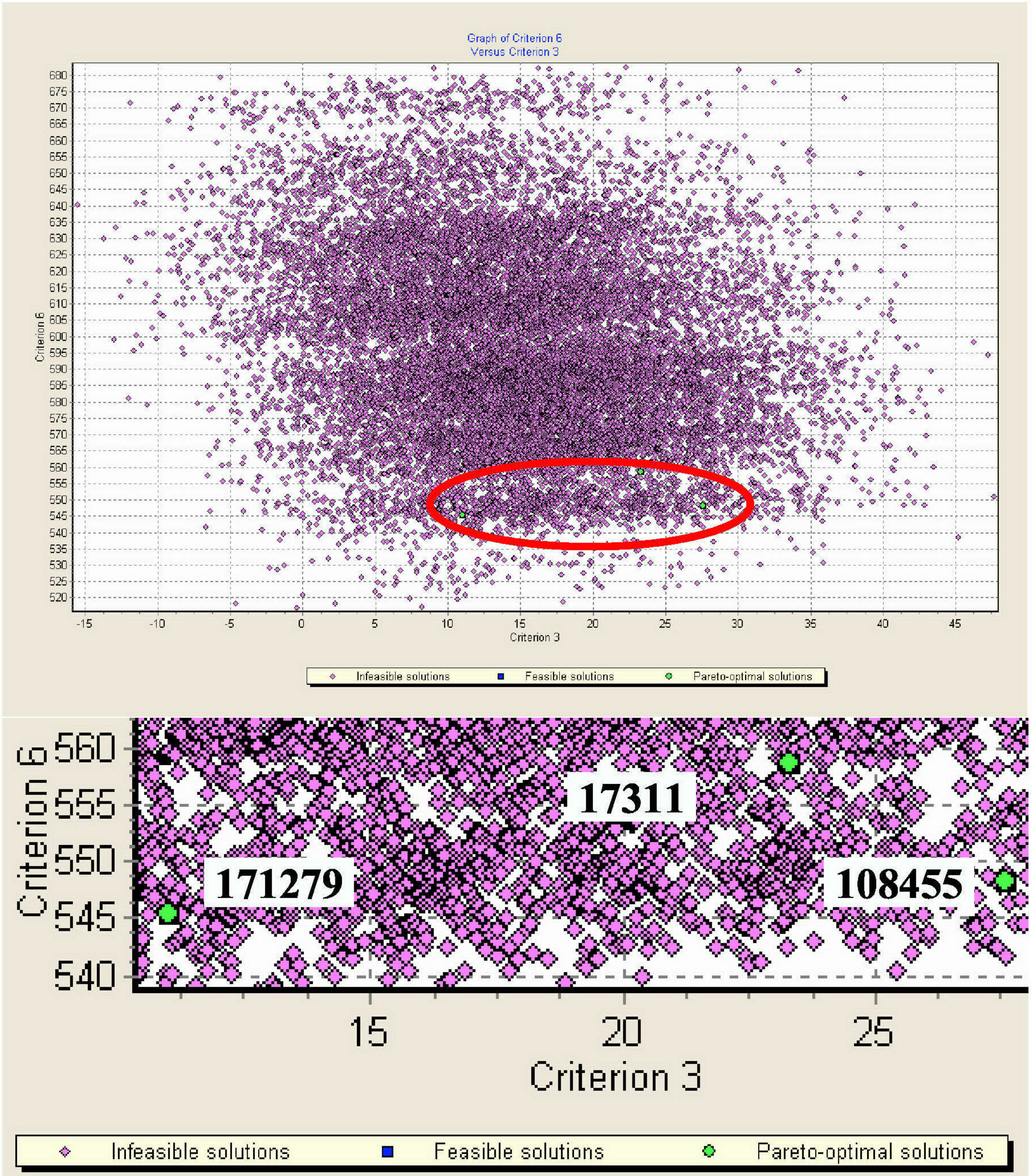

Figure 99 Criterion 3 (Maximized) vs. Criterion 6 (Minimized) – 3rd Optimization.

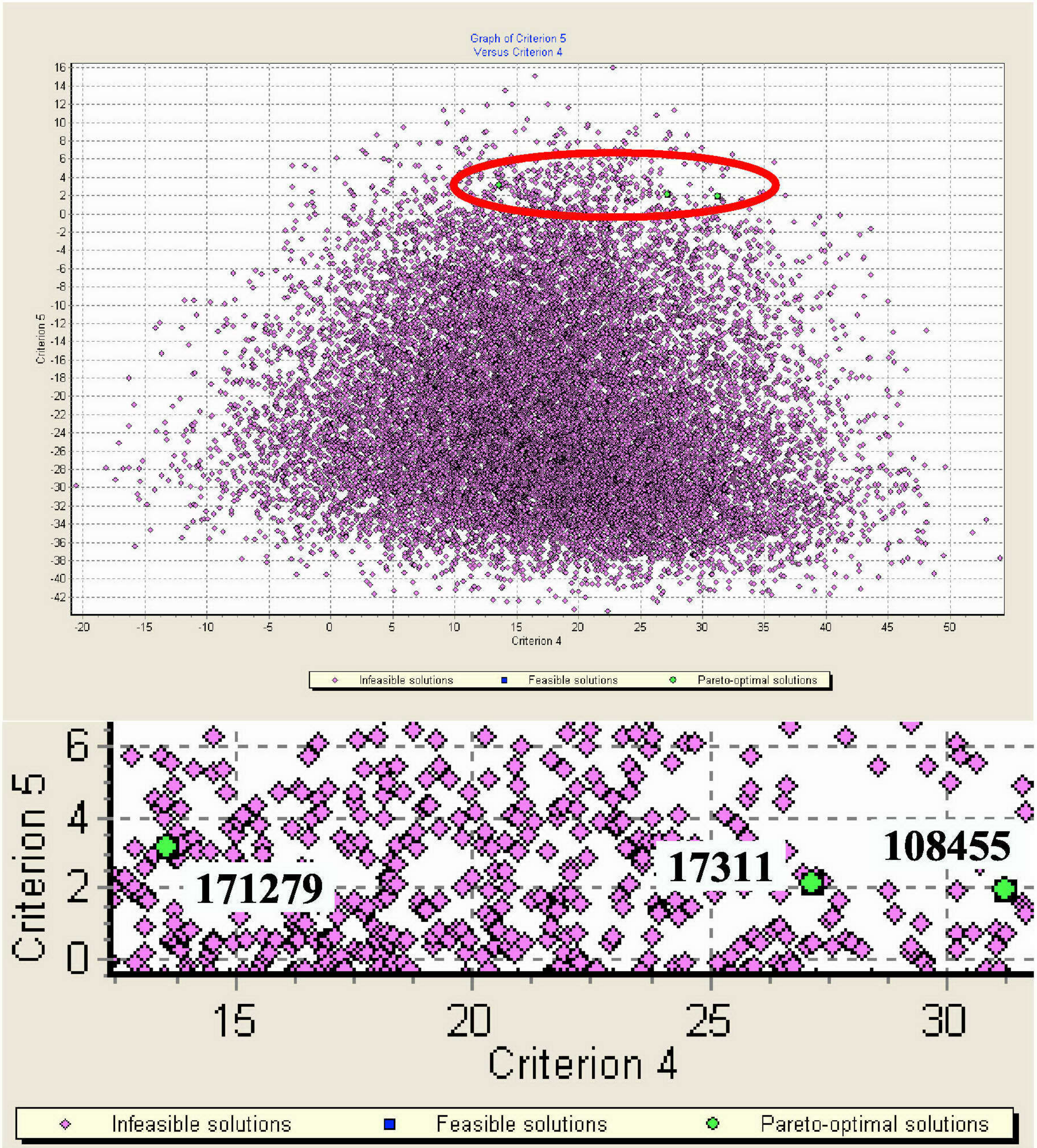

Figure 100 Criterion 4 (Maximized) vs. Criterion 5 (Maximized) – 3rd Optimization.

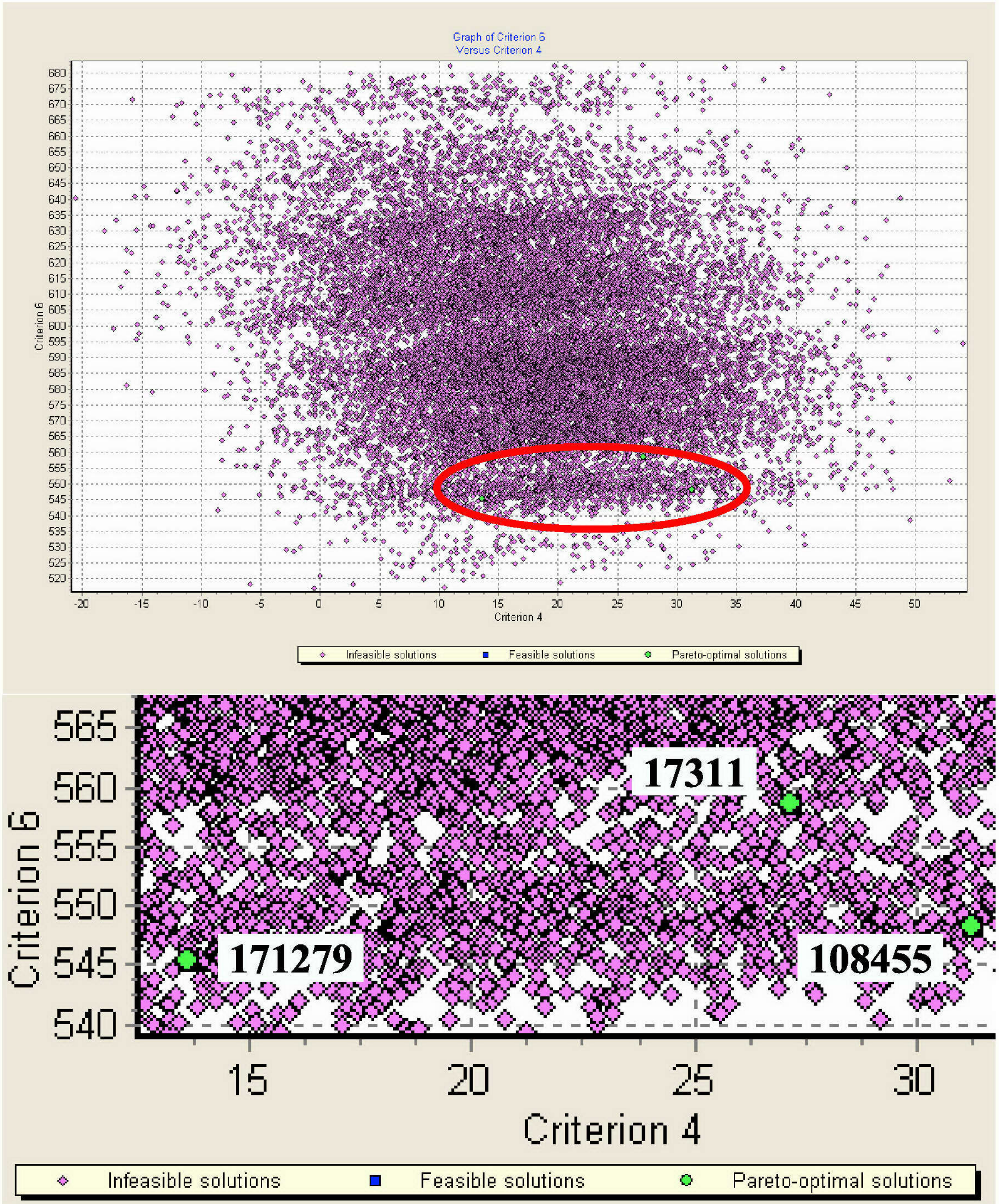

Figure 101 Criterion 4 (Maximized) vs. Criterion 6 (Minimized) – 3rd Optimization.

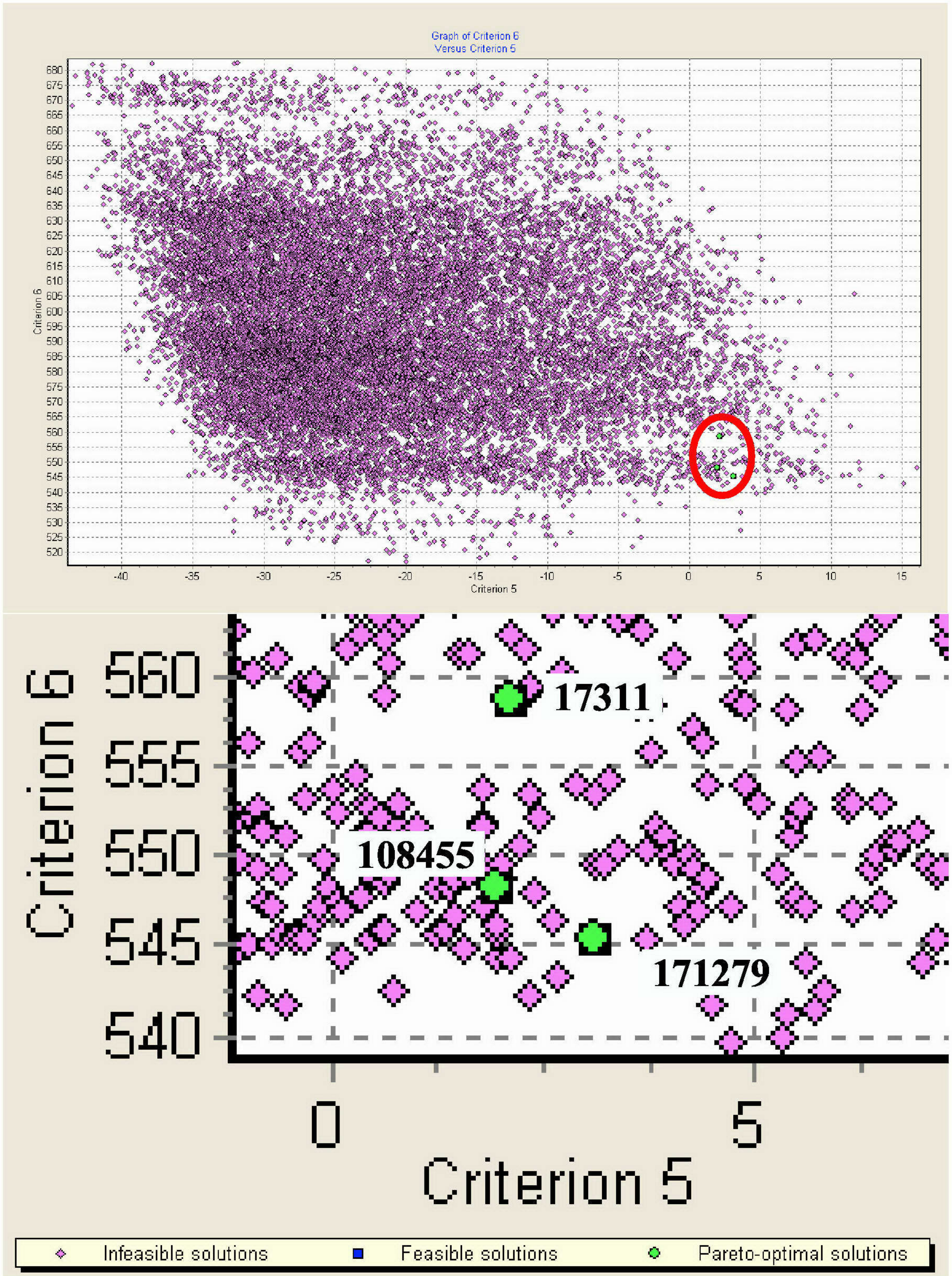

Figure 102 Criterion 5 (Maximized) vs. Criterion 6 (Minimized) – 3rd Optimization.

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APPENDIX K. CRITERION VS. CRITERION GRAPHS (MIT MODEL) – 4TH & 5TH OPTIMIZATIONS

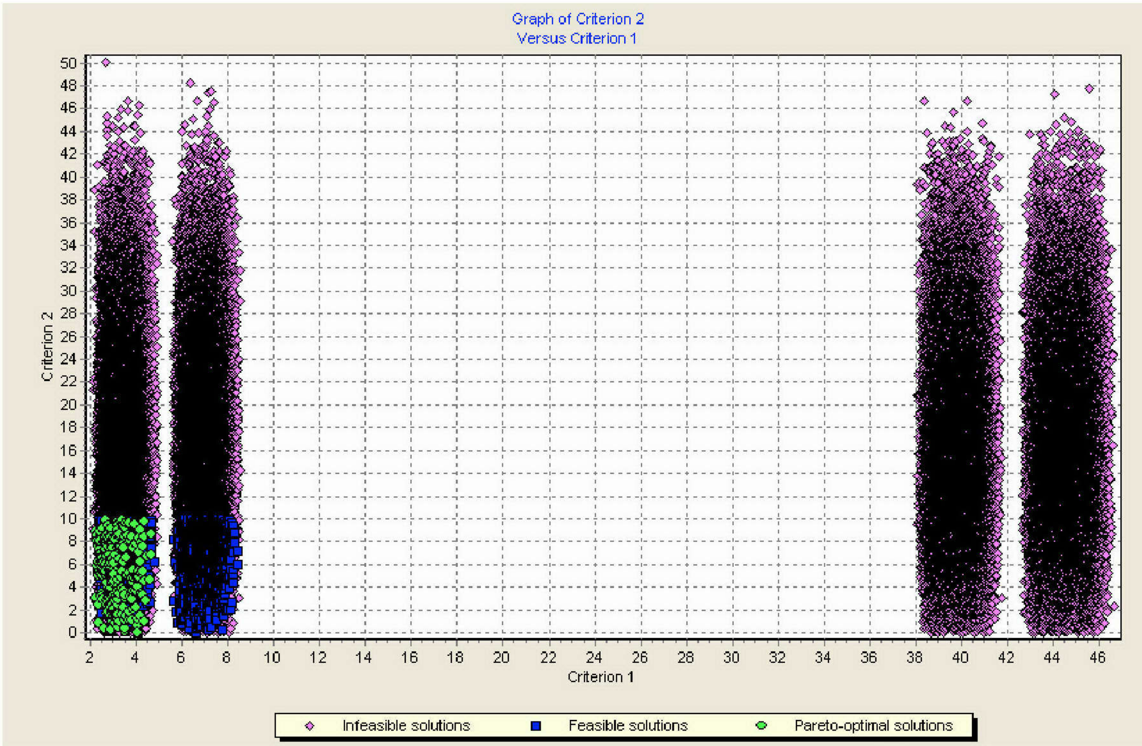

Figure 103 Criterion 1 (Minimized) vs. Criterion 2 (Minimized) – 4th Optimization.

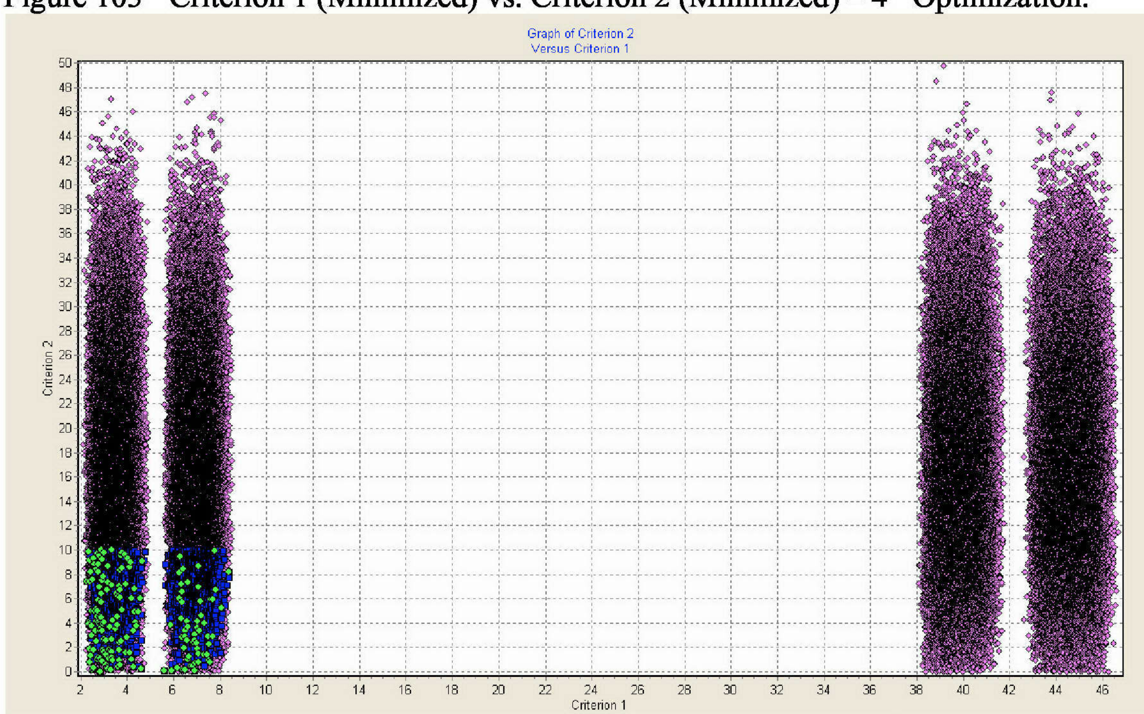

Figure 104 Criterion 1 (Minimized) vs. Criterion 2 (Minimized) – 5th Optimization.

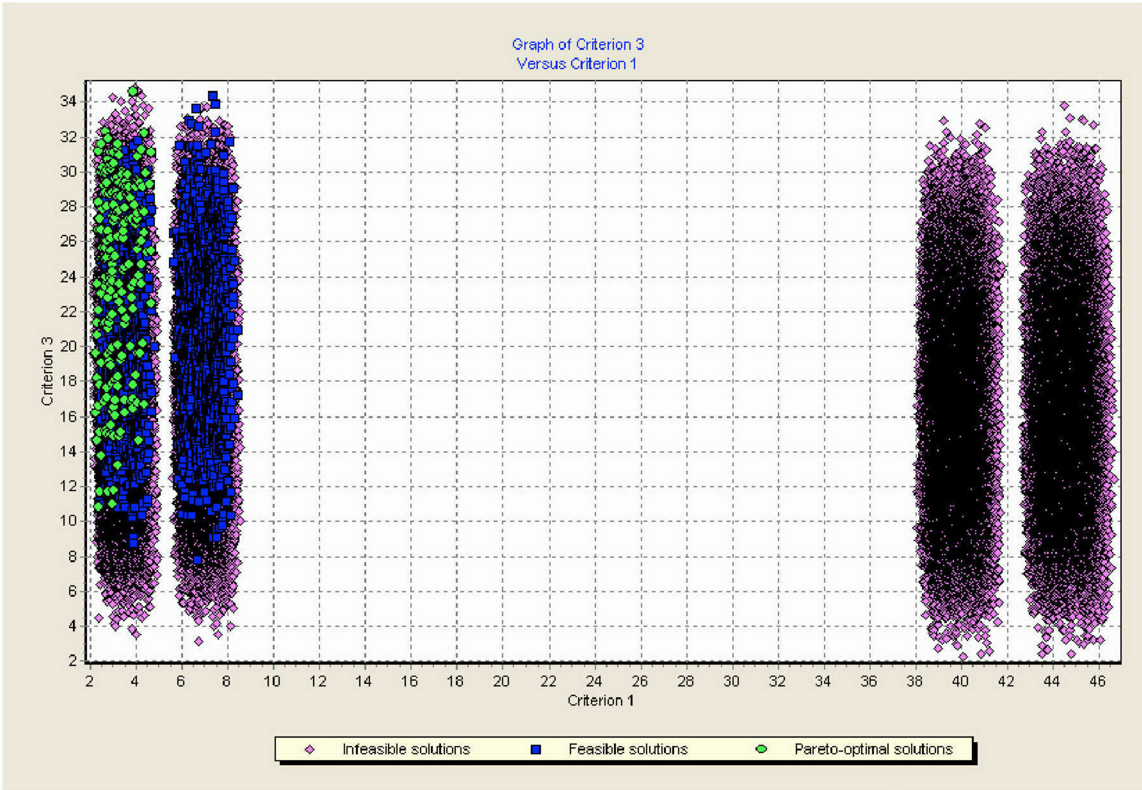

Figure 105 Criterion 1 (Minimized) vs. Criterion 3 (Maximized) – 4th Optimization.

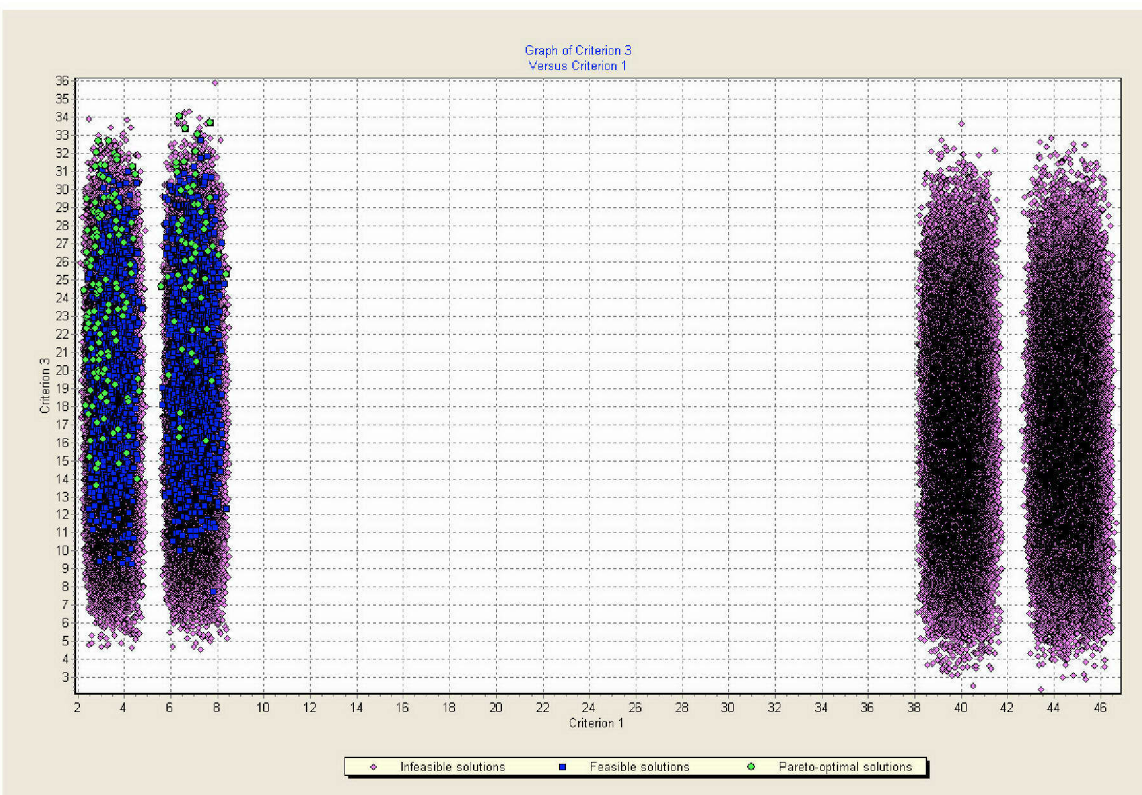

Figure 106 Criterion 1 (Minimized) vs. Criterion 3 (Maximized) – 5th Optimization.

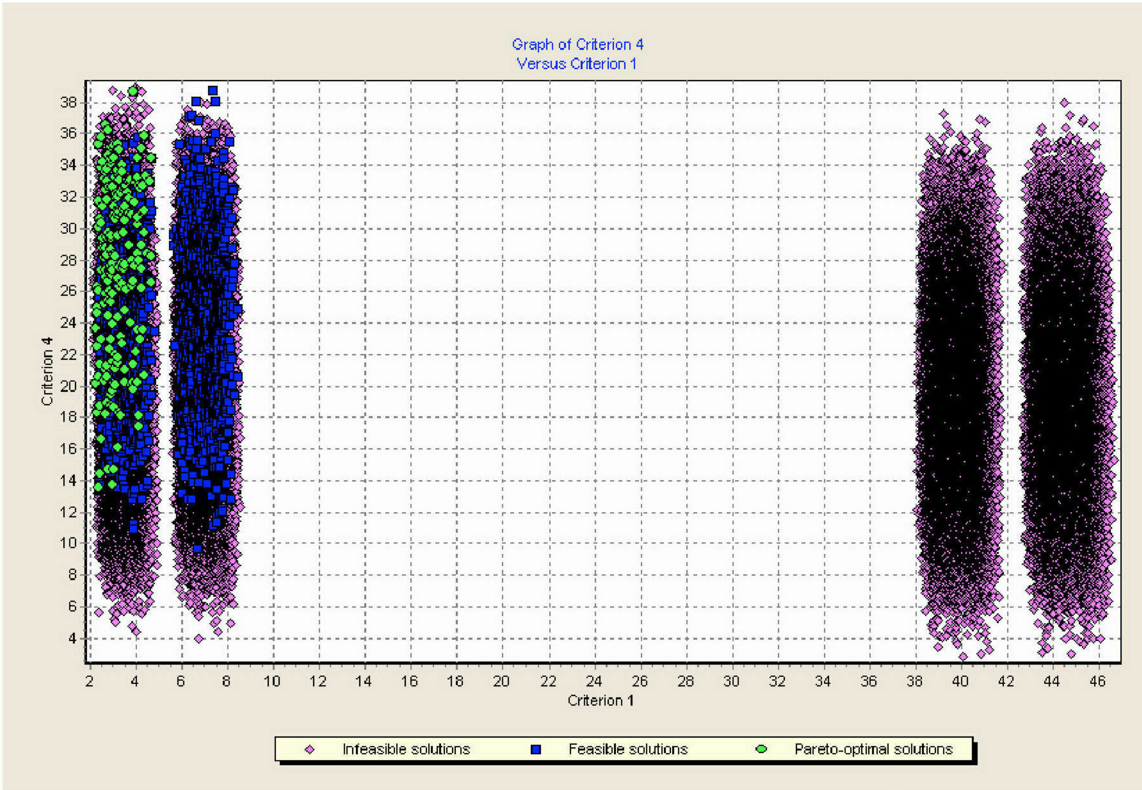

Figure 107 Criterion 1 (Minimized) vs. Criterion 4 (Maximized) – 4th Optimization.

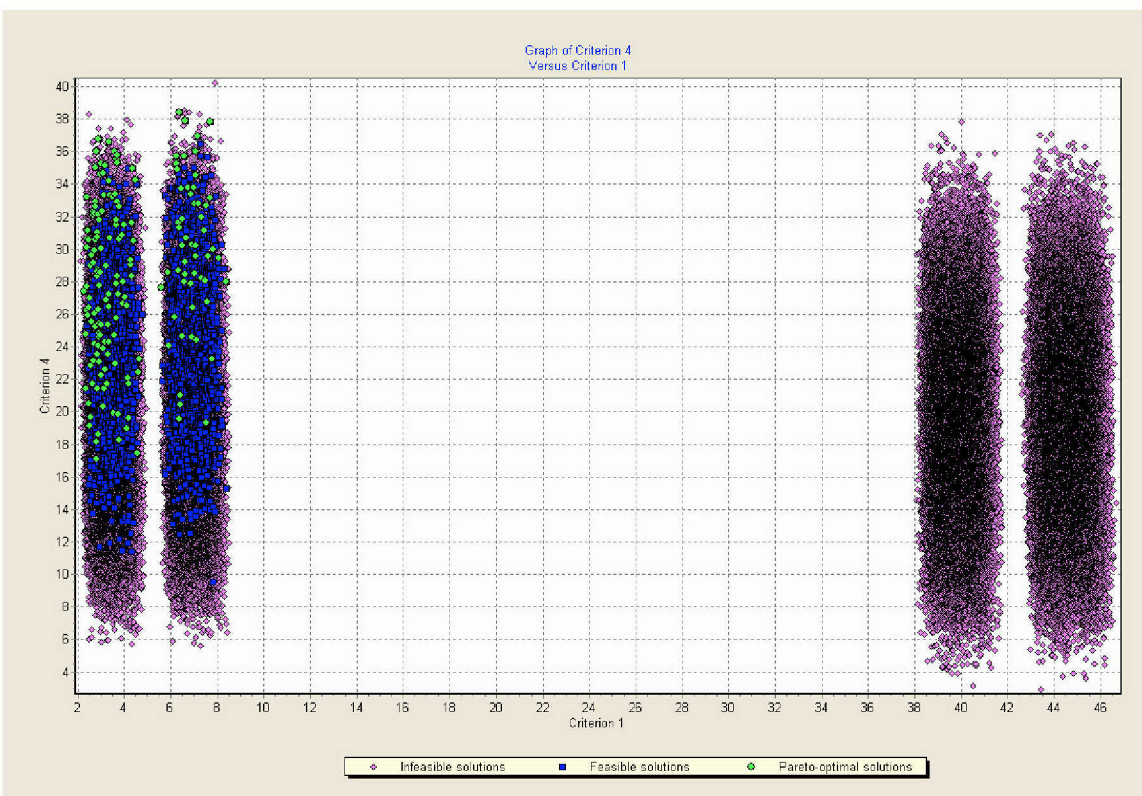

Figure 108 Criterion 1 (Minimized) vs. Criterion 4 (Maximized) – 5th Optimization.

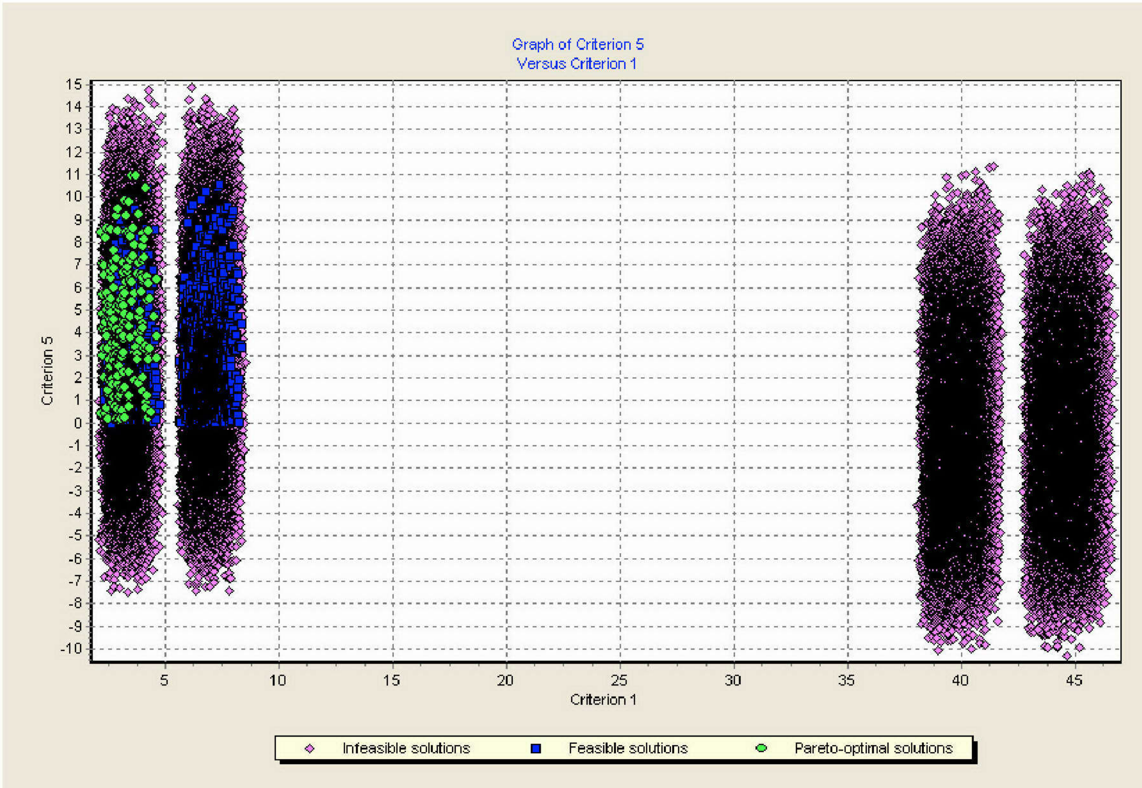

Figure 109 Criterion 1 (Minimized) vs. Criterion 5 (Maximized) – 4th Optimization.

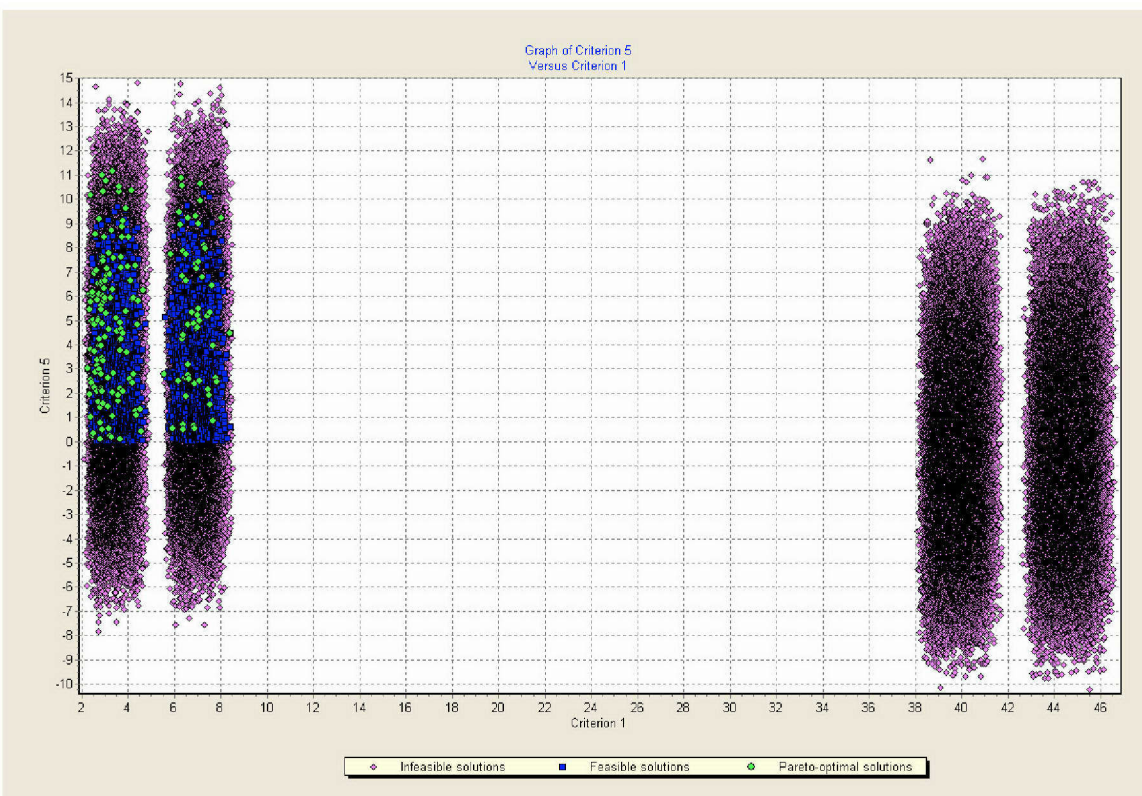

Figure 110 Criterion 1 (Minimized) vs. Criterion 5 (Maximized) – 5th Optimization.

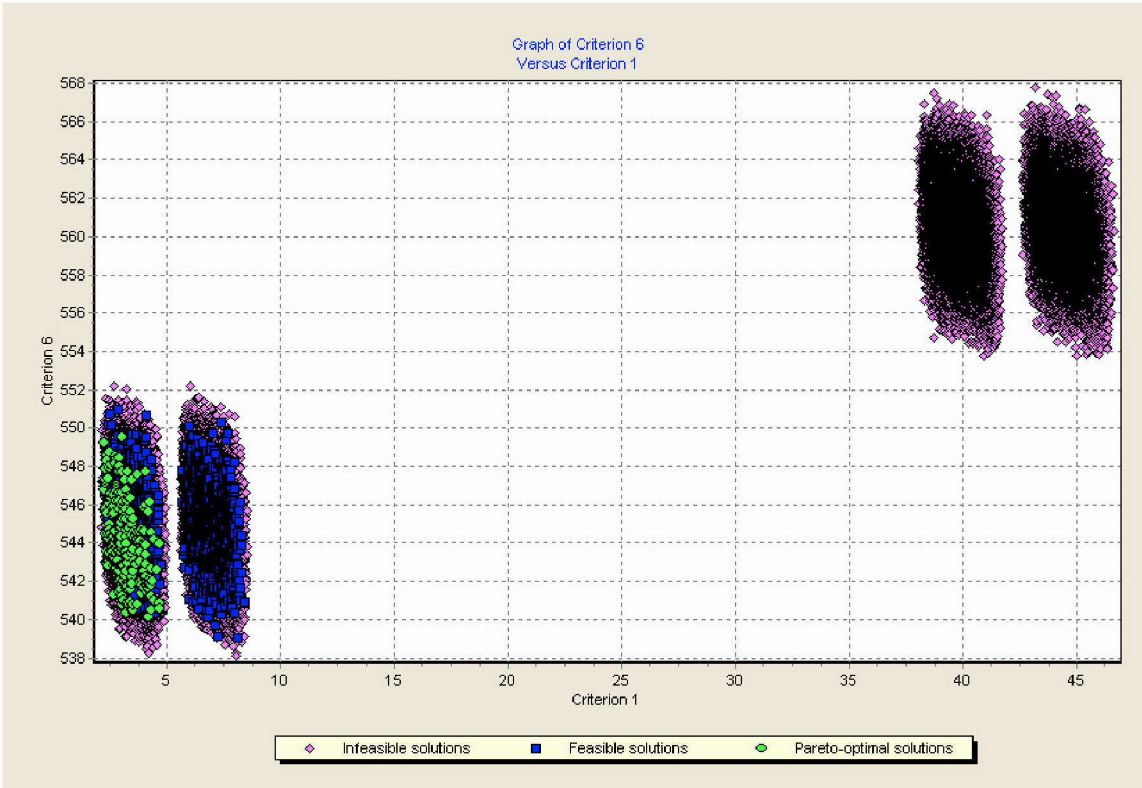

Figure 111 Criterion 1 (Minimized) vs. Criterion 6 (Minimized) – 4th Optimization.

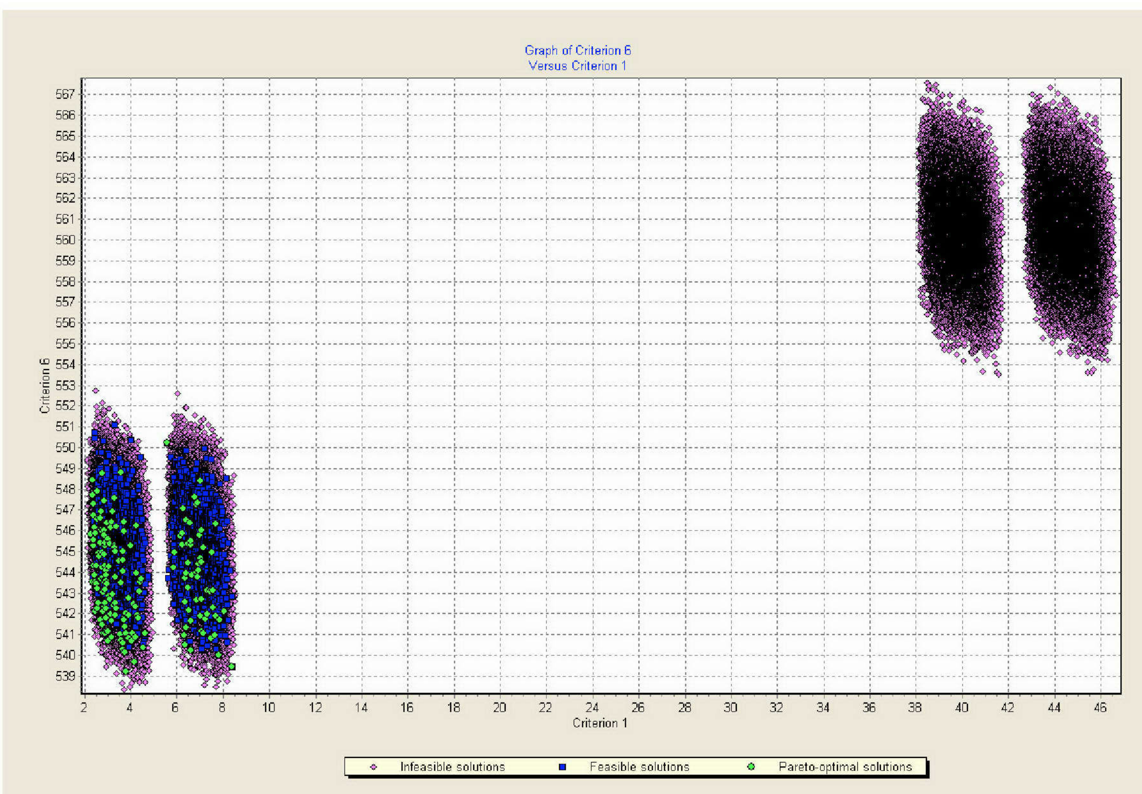

Figure 112 Criterion 1 (Minimized) vs. Criterion 6 (Minimized) – 5th Optimization.

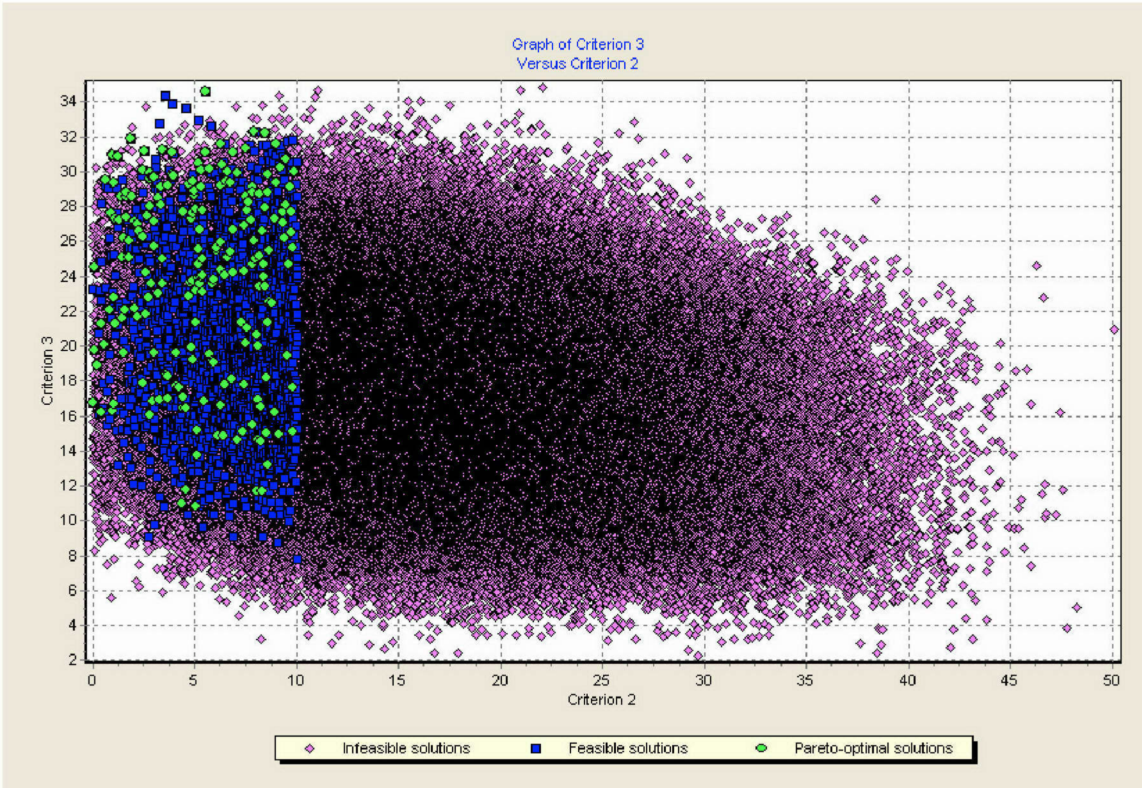

Figure 113 Criterion 2 (Minimized) vs. Criterion 3 (Maximized) – 4th Optimization.

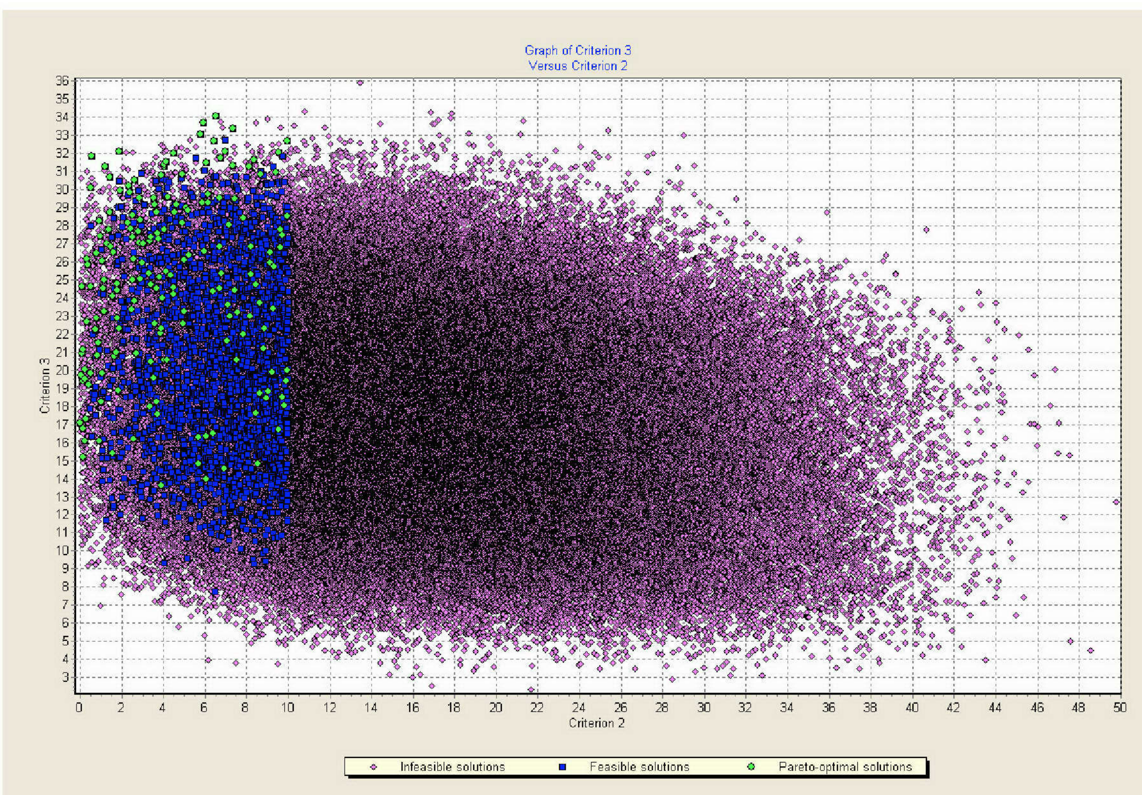

Figure 114 Criterion 2 (Minimized) vs. Criterion 3 (Maximized) – 5th Optimization.

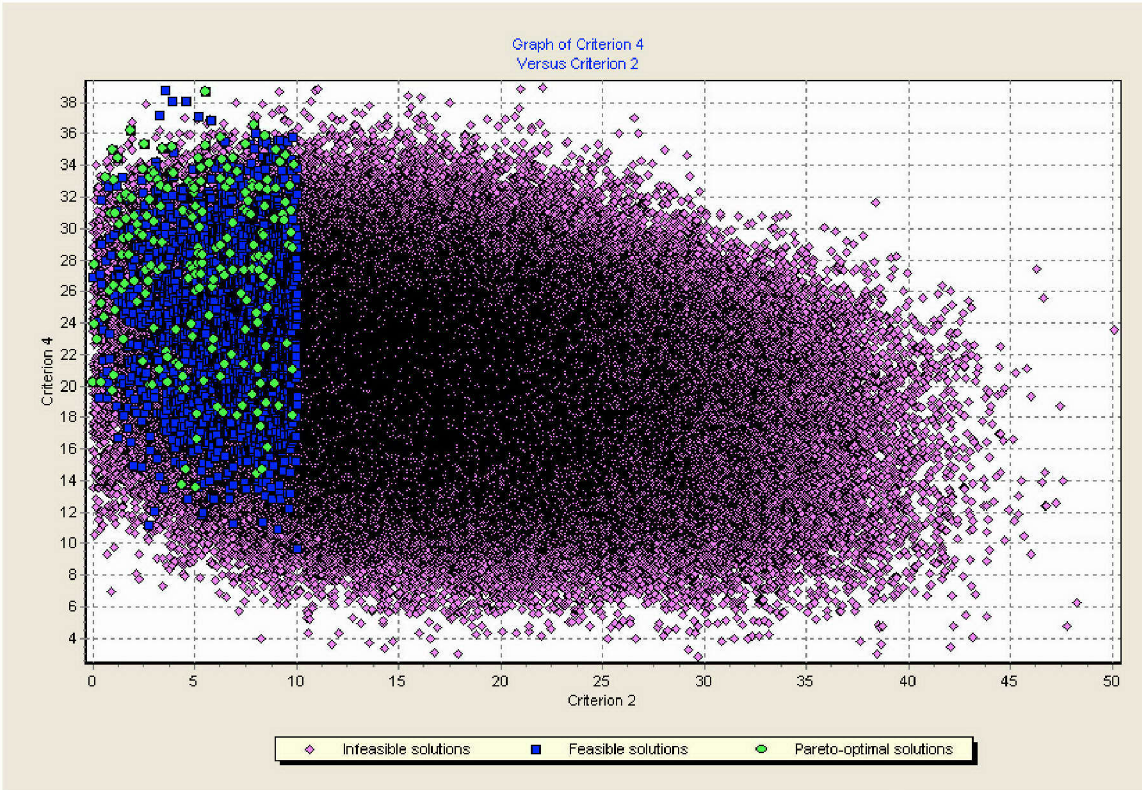

Figure 115 Criterion 2 (Minimized) vs. Criterion 4 (Maximized) – 4th Optimization.

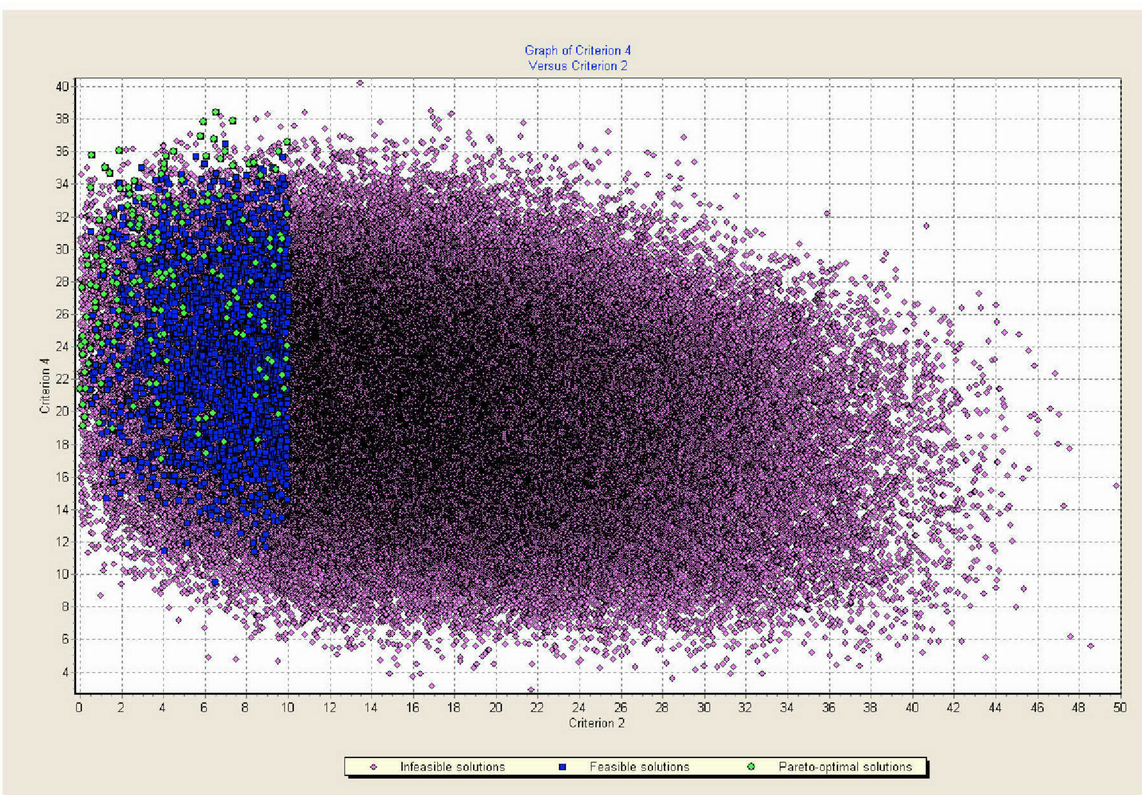

Figure 116 Criterion 2 (Minimized) vs. Criterion 4 (Maximized) – 5th Optimization.

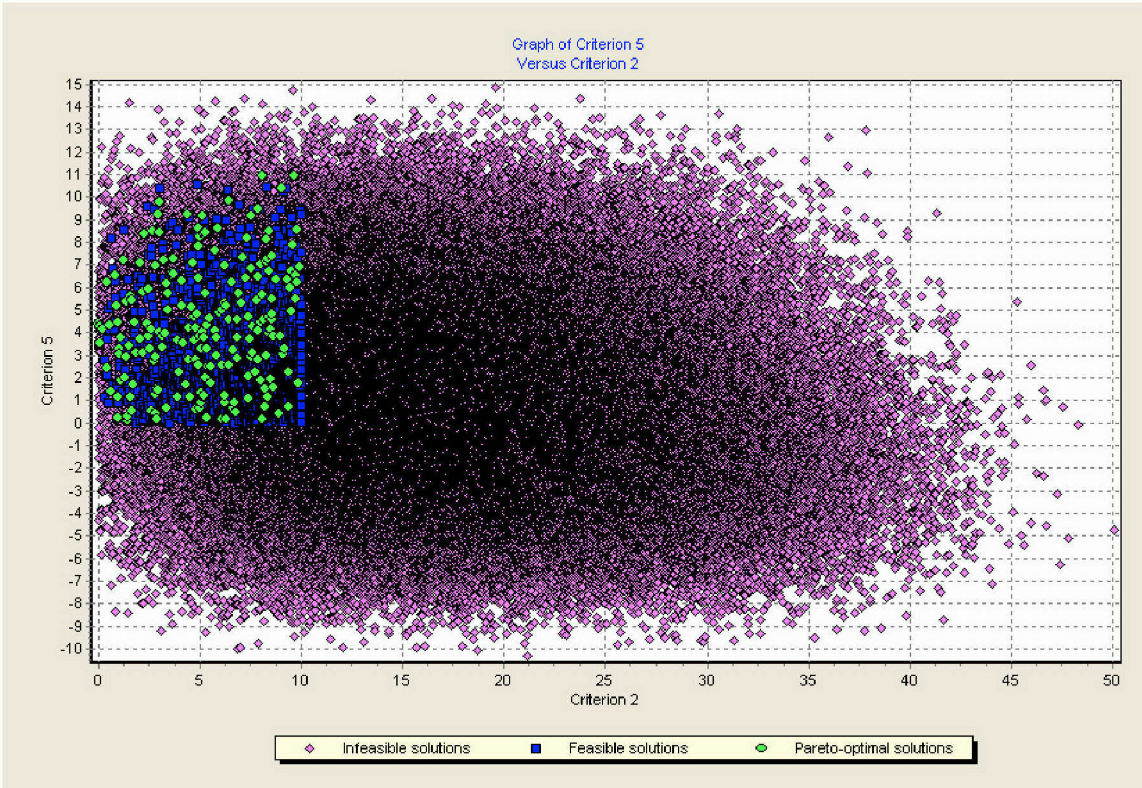

Figure 117 Criterion 2 (Minimized) vs. Criterion 5 (Maximized) – 4th Optimization.

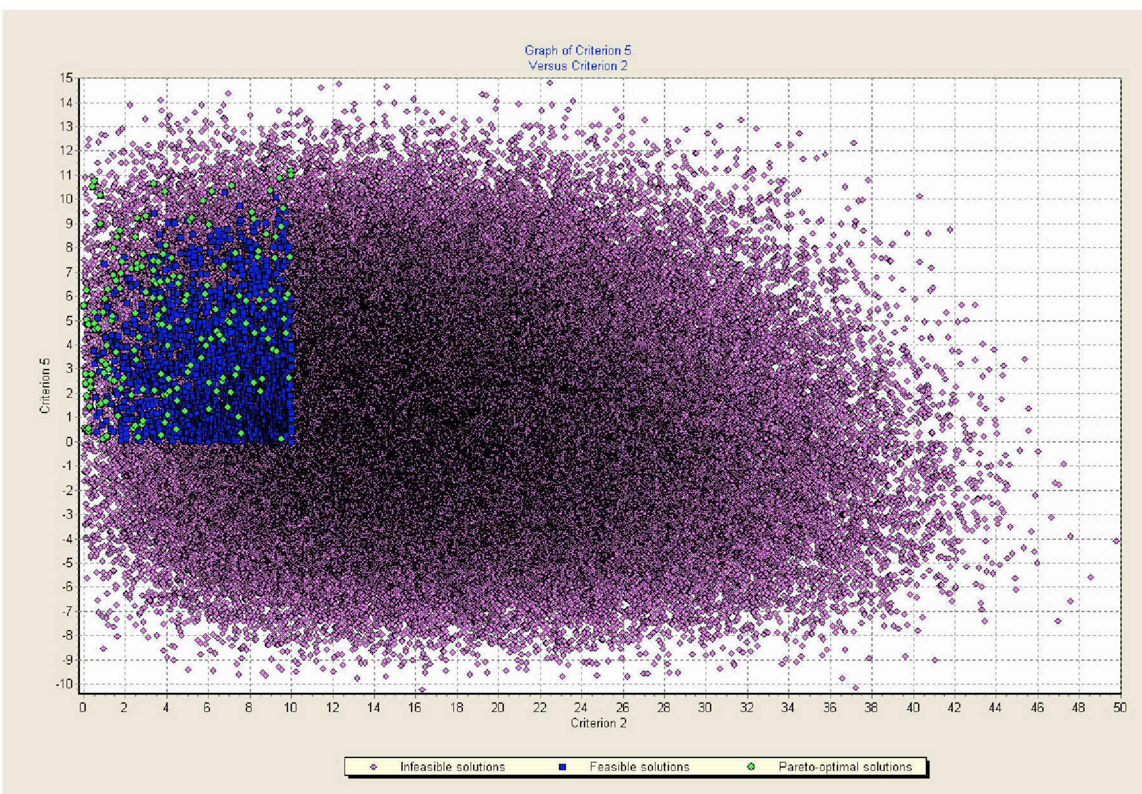

Figure 118 Criterion 2 (Minimized) vs. Criterion 5 (Maximized) – 5th Optimization.

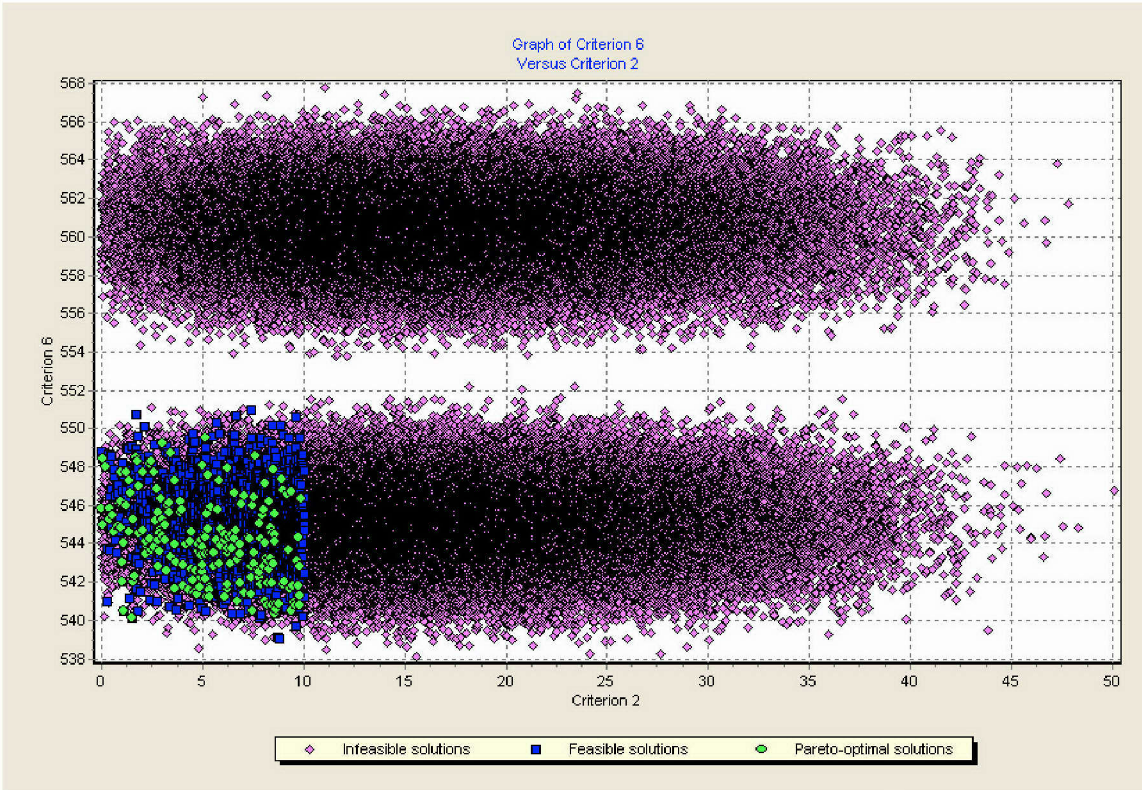

Figure 119 Criterion 2 (Minimized) vs. Criterion 6 (Minimized) – 4th Optimization.

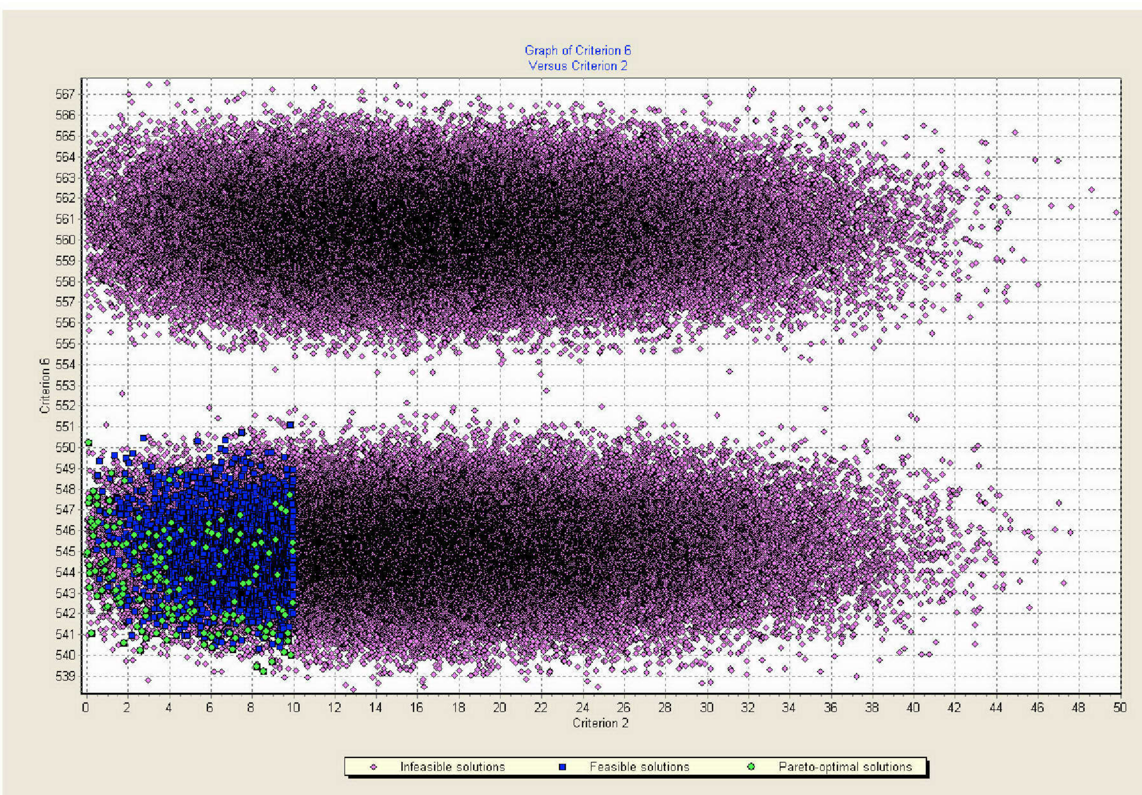

Figure 120 Criterion 2 (Minimized) vs. Criterion 6 (Minimized) – 5th Optimization.

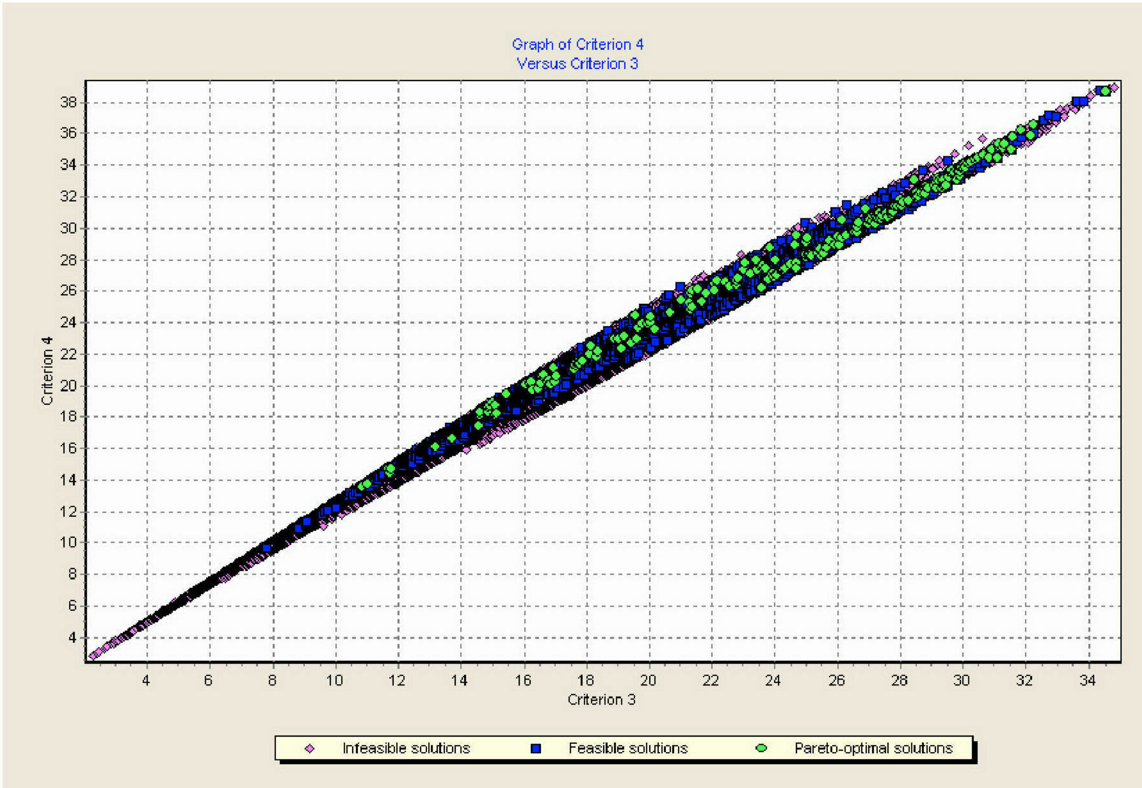

Figure 121 Criterion 3 (Maximized) vs. Criterion 4 (Maximized) – 4th Optimization.

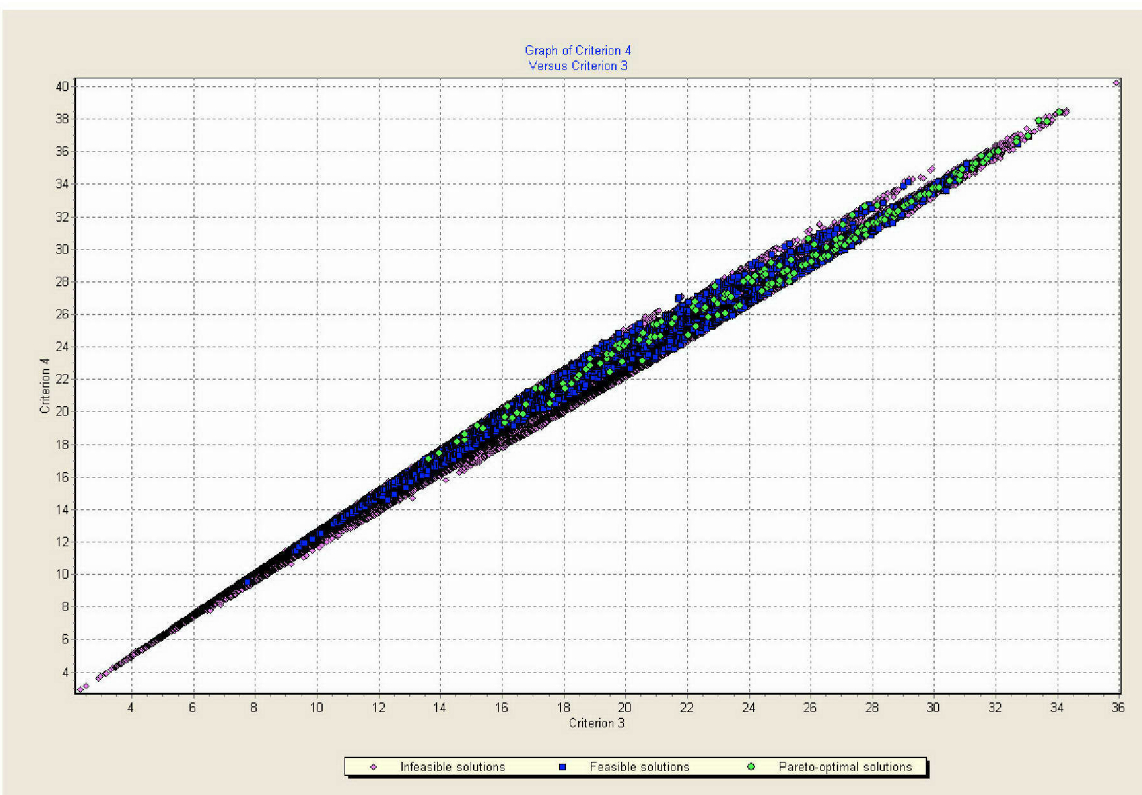

Figure 122 Criterion 3 (Maximized) vs. Criterion 4 (Maximized) – 5th Optimization.

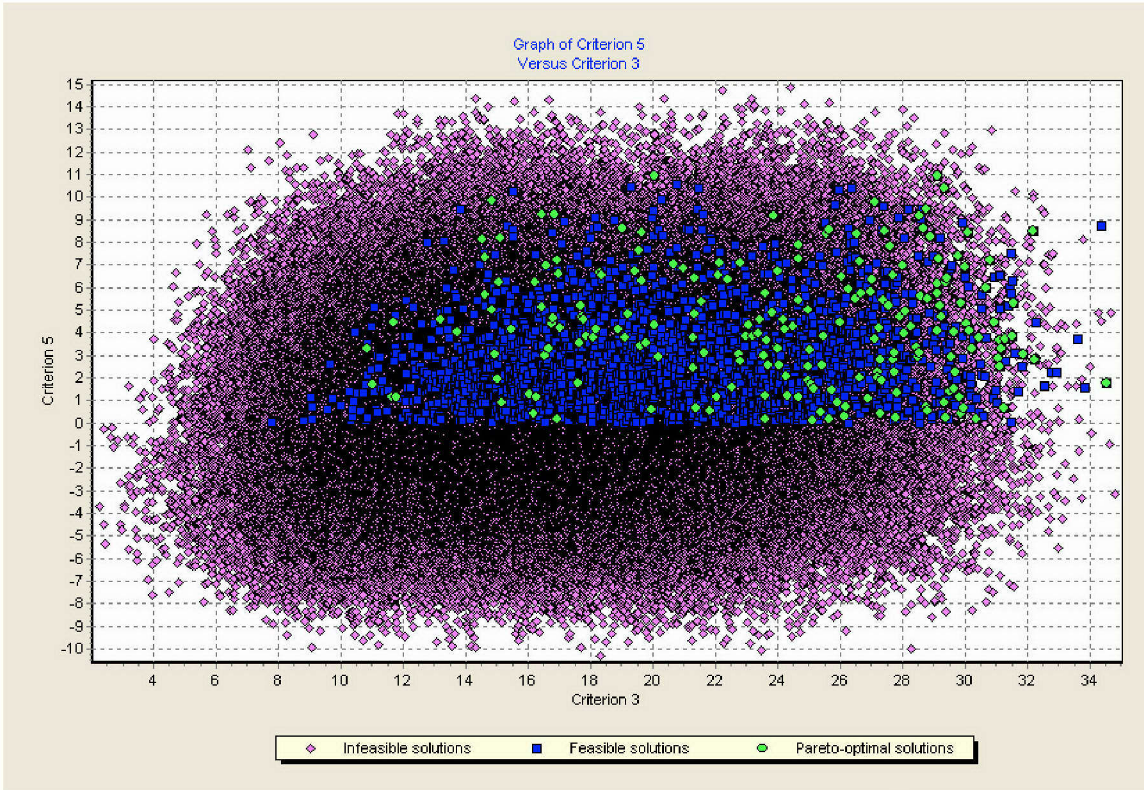

Figure 123 Criterion 3 (Maximized) vs. Criterion 5 (Maximized) – 4th Optimization.

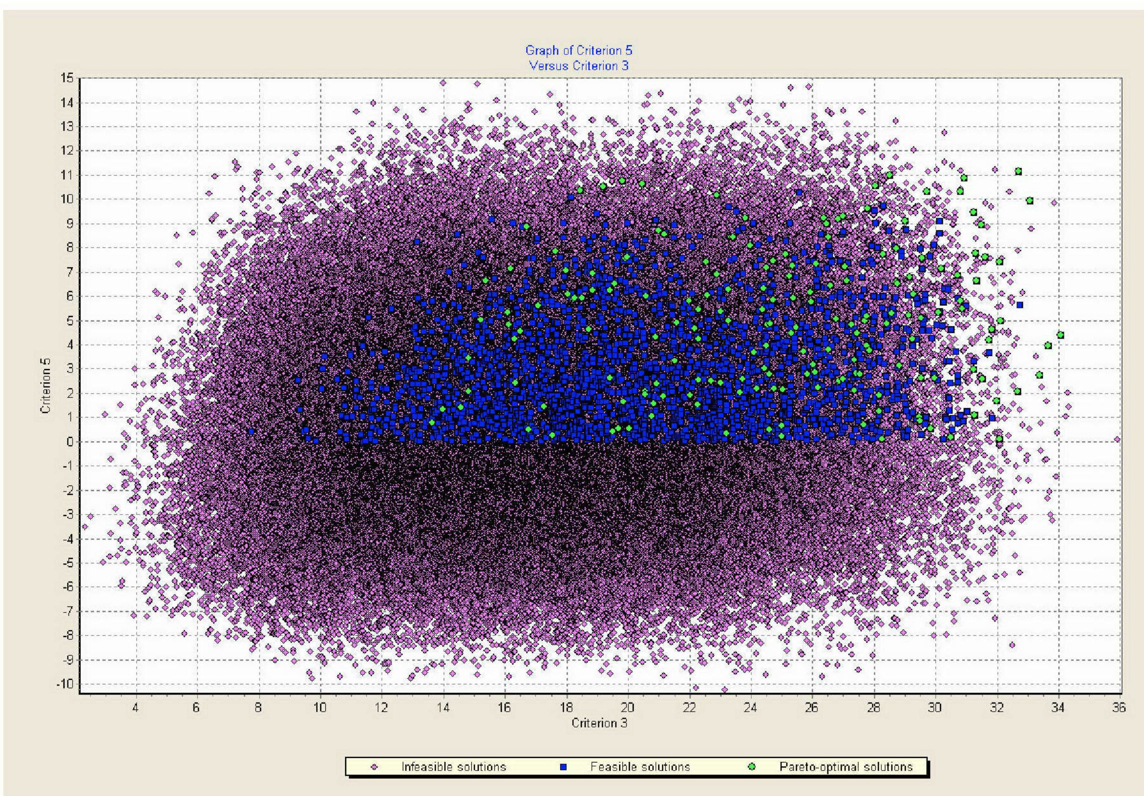

Figure 124 Criterion 3 (Maximized) vs. Criterion 5 (Maximized) – 5th Optimization.

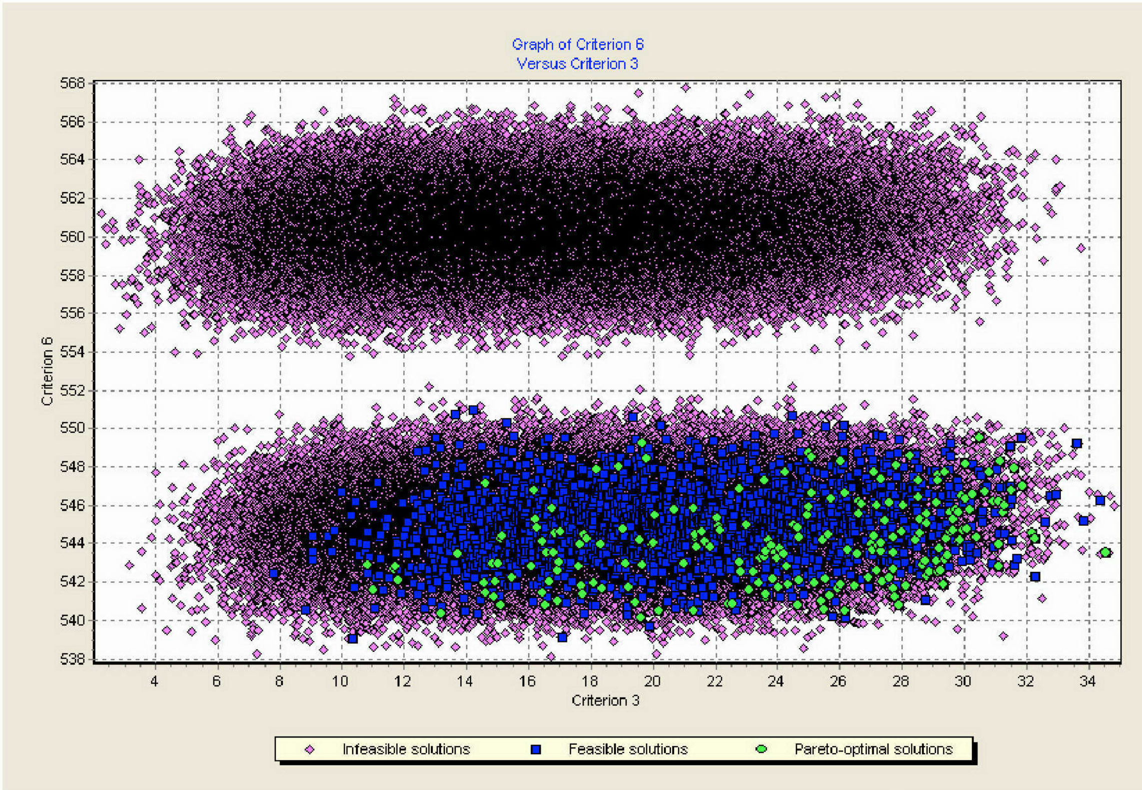

Figure 125 Criterion 3 (Maximized) vs. Criterion 6 (Minimized) – 4th Optimization.

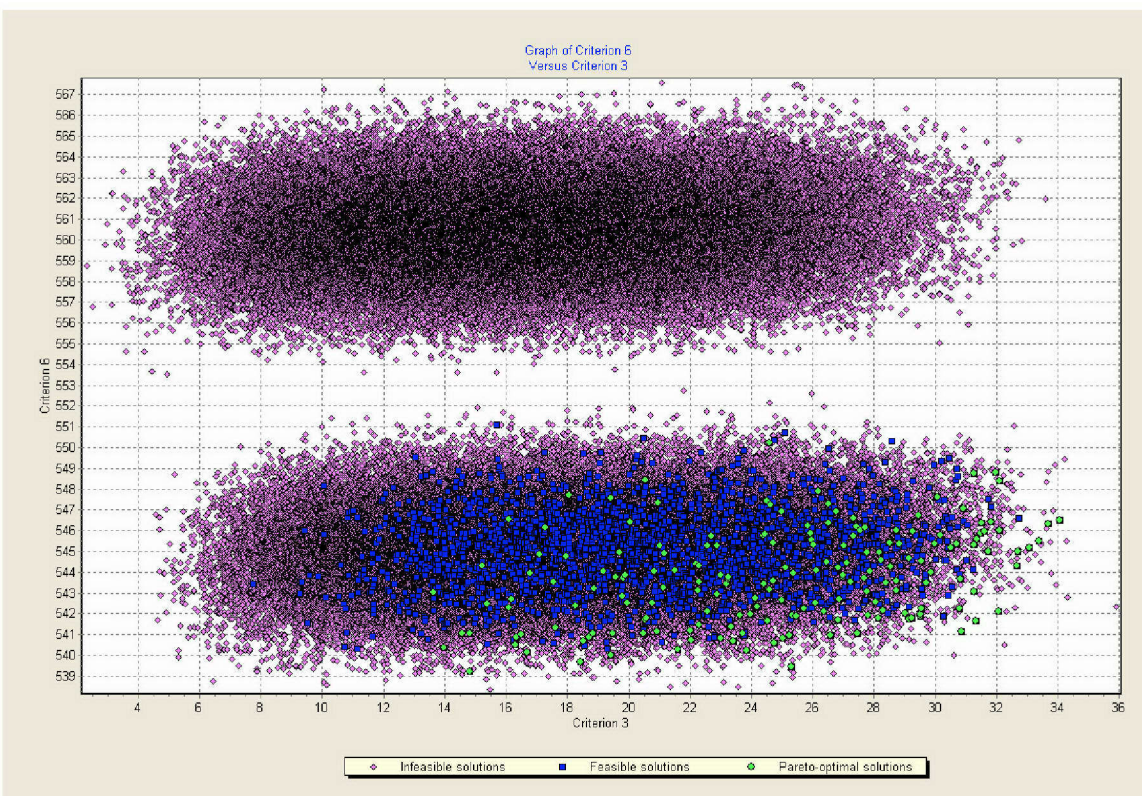

Figure 126 Criterion 3 (Maximized) vs. Criterion 6 (Minimized) – 5th Optimization.

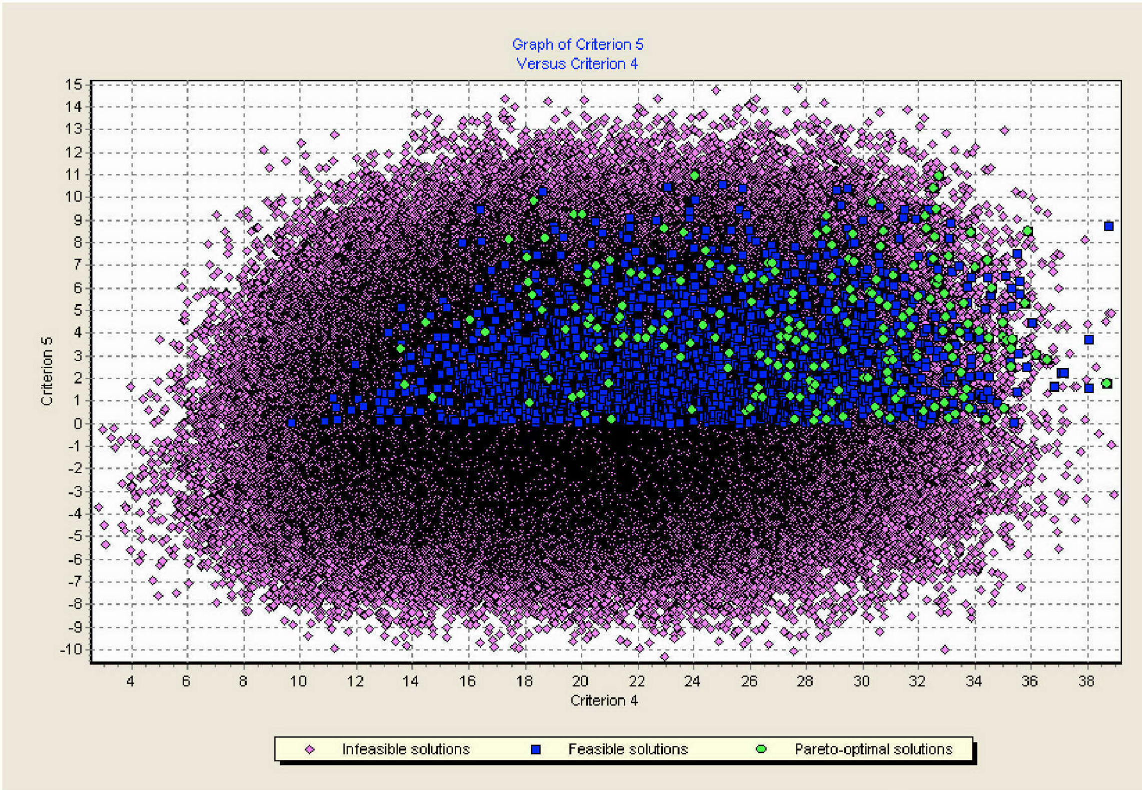

Figure 127 Criterion 4 (Maximized) vs. Criterion 5 (Maximized) – 4th Optimization.

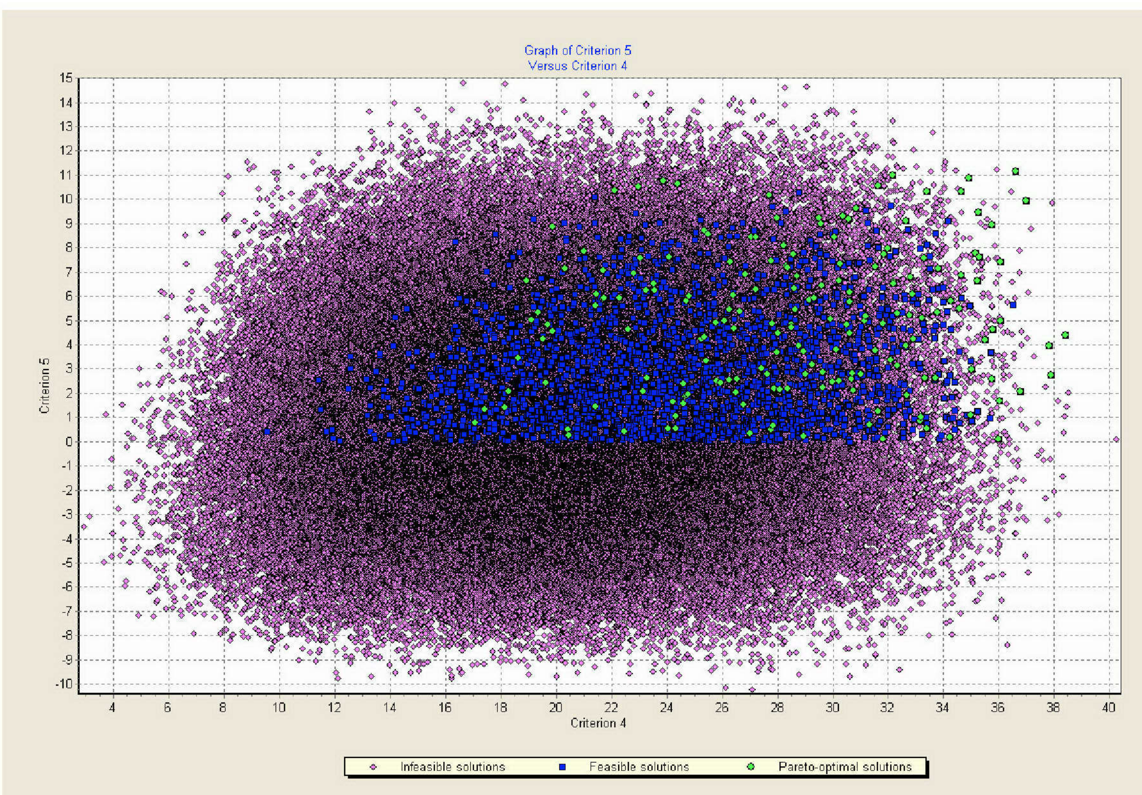

Figure 128 Criterion 4 (Maximized) vs. Criterion 5 (Maximized) – 5th Optimization.

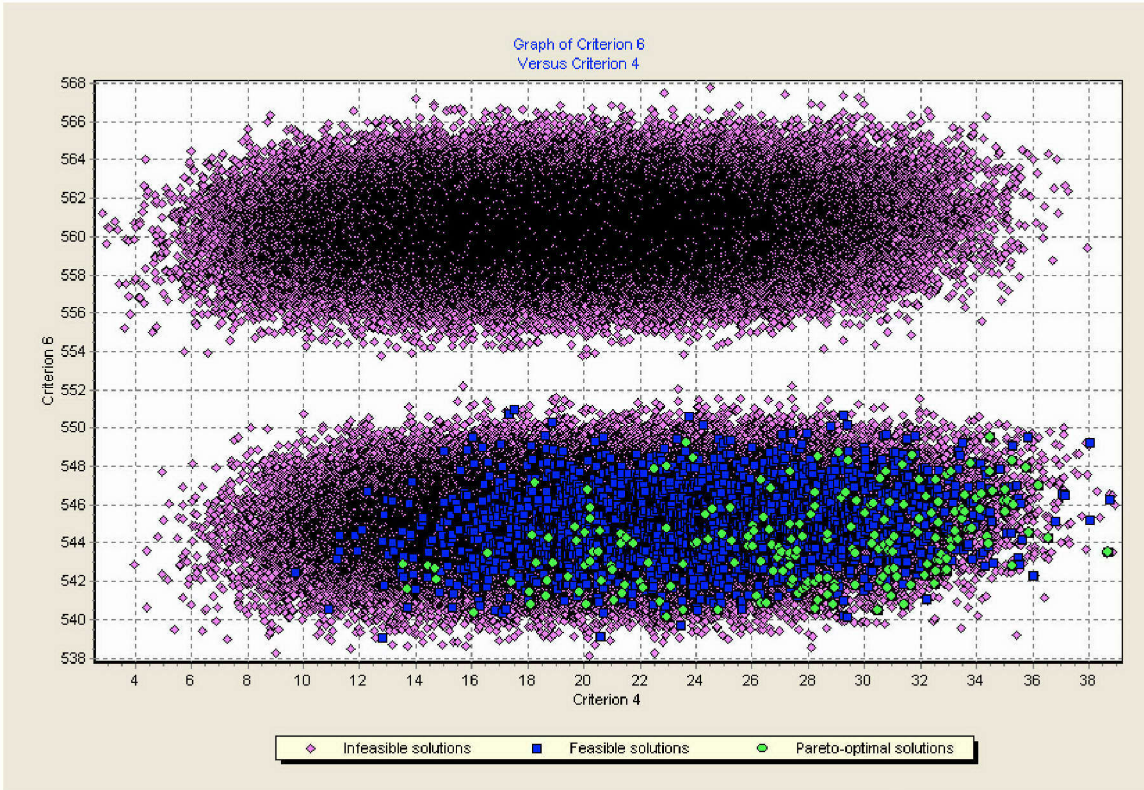

Figure 129 Criterion 4 (Maximized) vs. Criterion 6 (Minimized) – 4th Optimization.

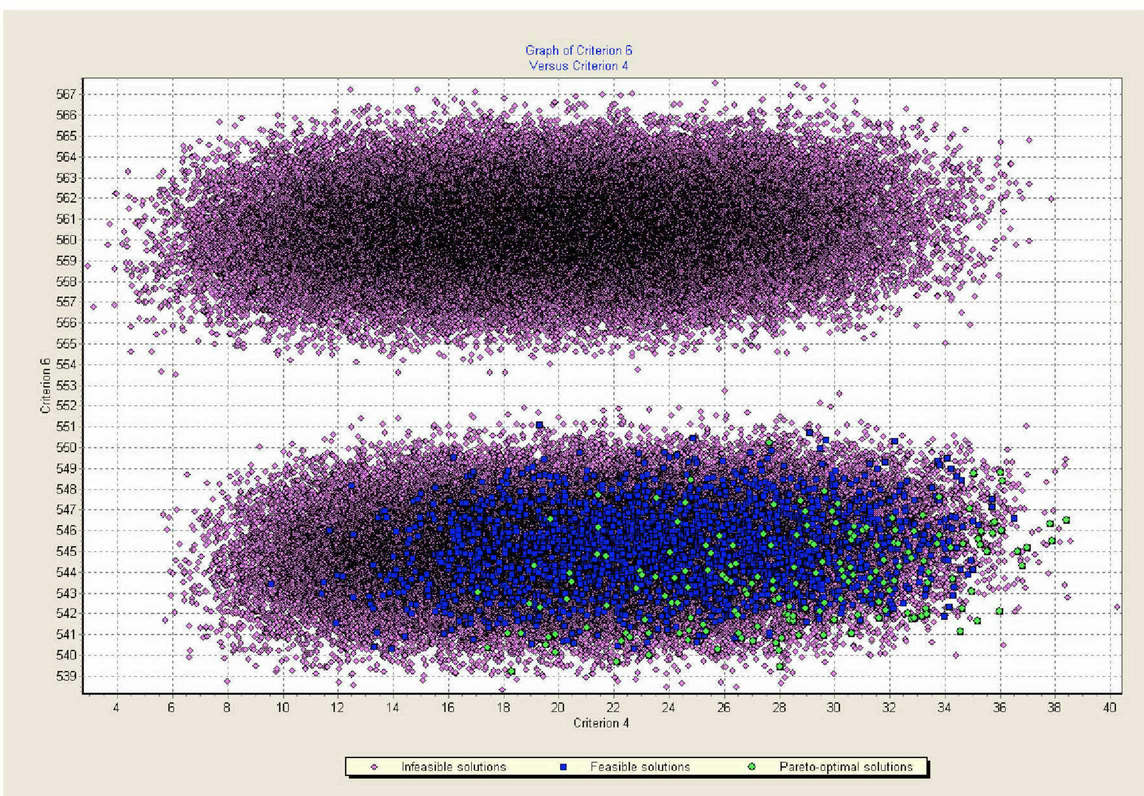

Figure 130 Criterion 4 (Maximized) vs. Criterion 6 (Minimized) – 5th Optimization.

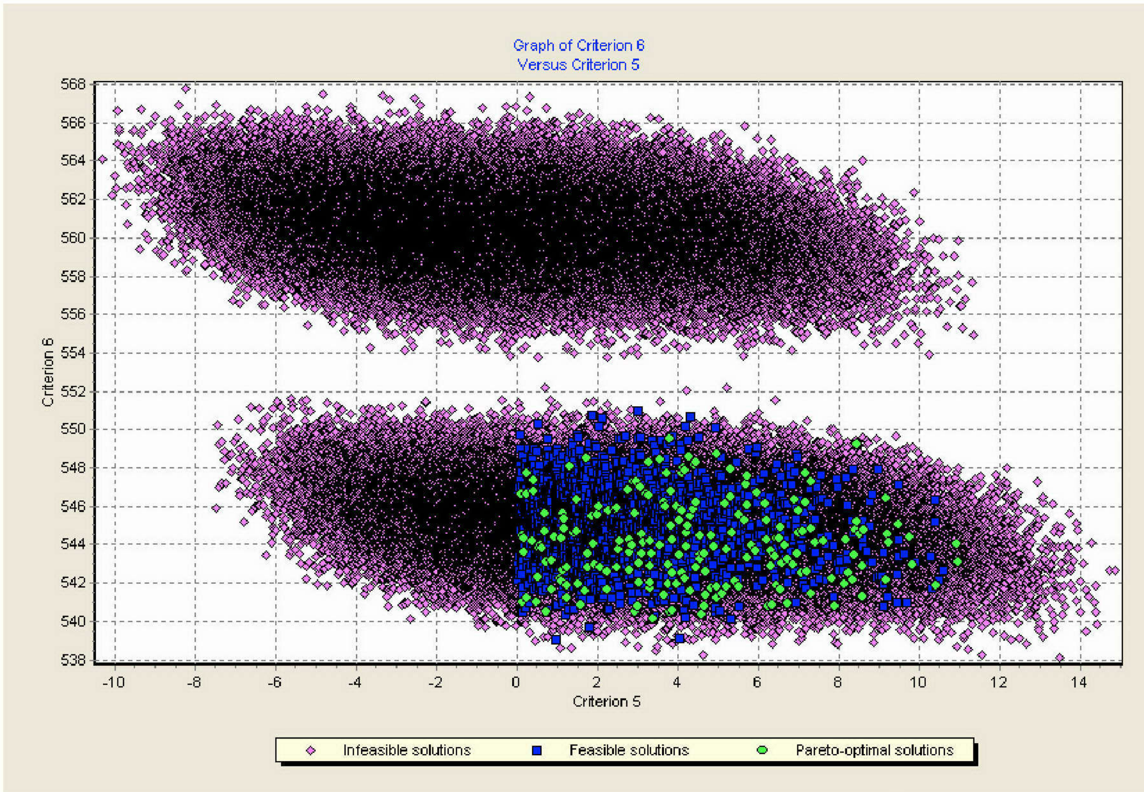

Figure 131 Criterion 5 (Maximized) vs. Criterion 6 (Minimized) – 4th Optimization.

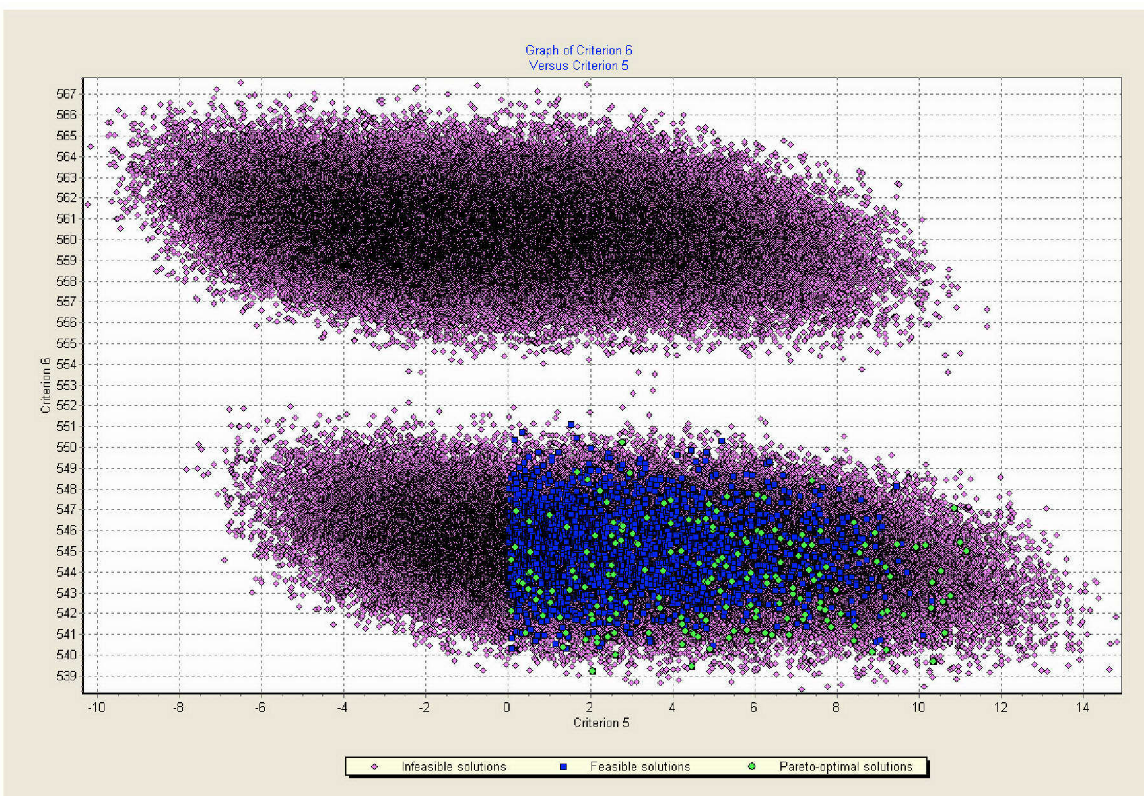

Figure 132 Criterion 5 (Maximized) vs. Criterion 6 (Minimized) – 5th Optimization.

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APPENDIX L. CRITERION VS. CRITERION GRAPHS (MIT MODEL) – 6TH OPTIMIZATION

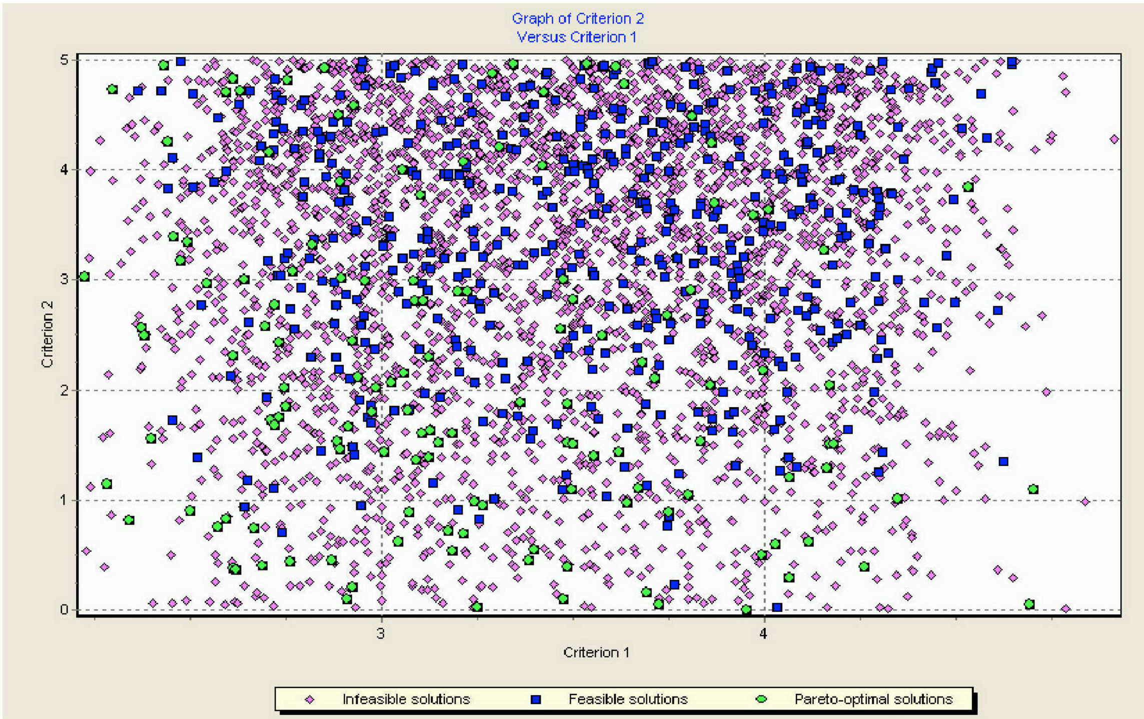

Figure 133 Criterion 1 (Minimized) vs. Criterion 2 (Minimized) – 6th Optimization.

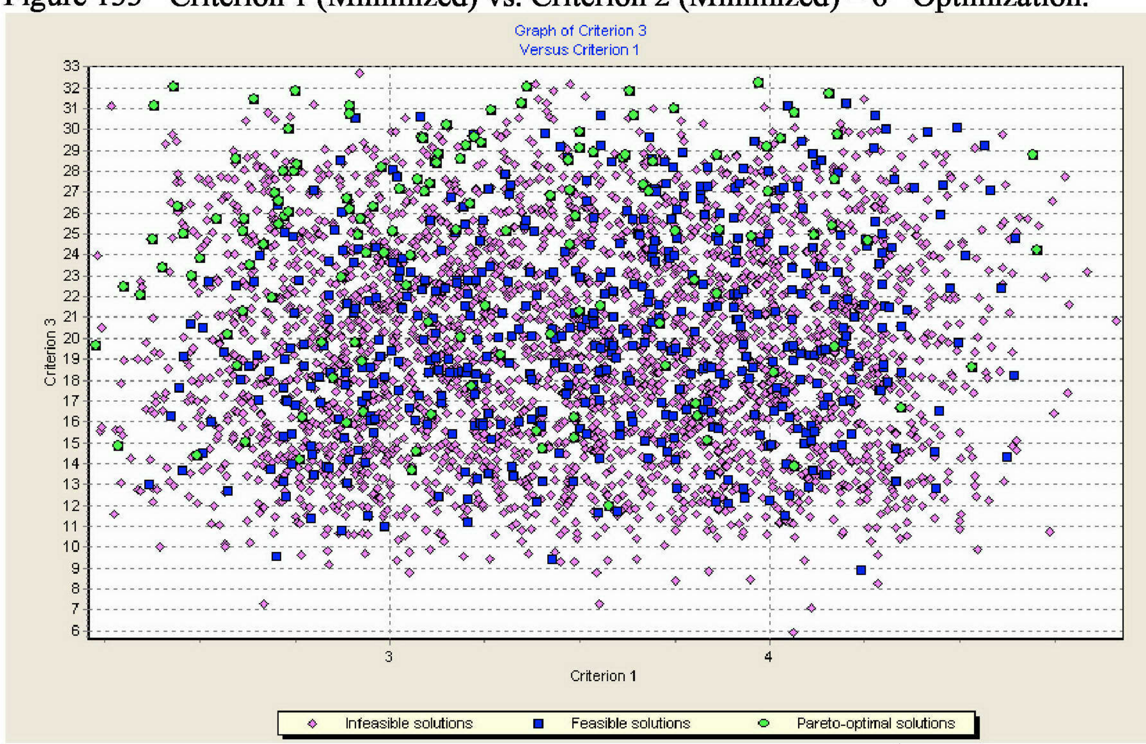

Figure 134 Criterion 1 (Minimized) vs. Criterion 3 (Maximized) – 6th Optimization.

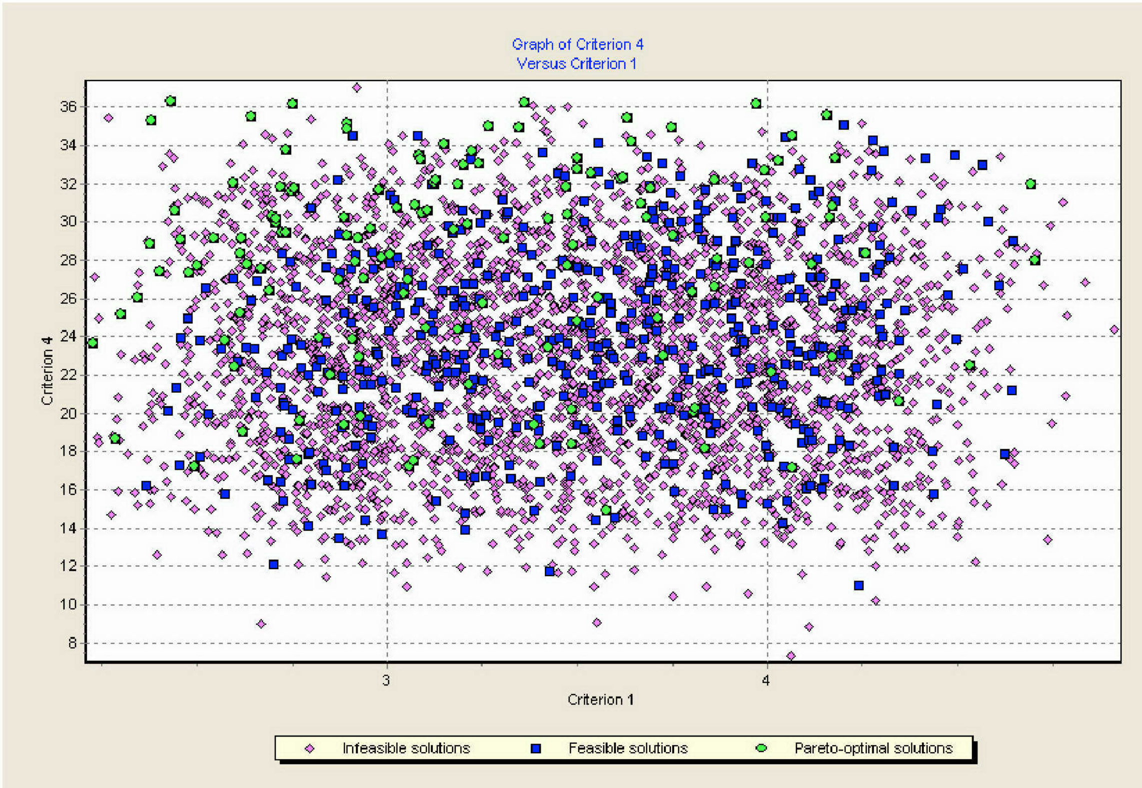

Figure 135 Criterion 1 (Minimized) vs. Criterion 4 (Maximized) – 6th Optimization.

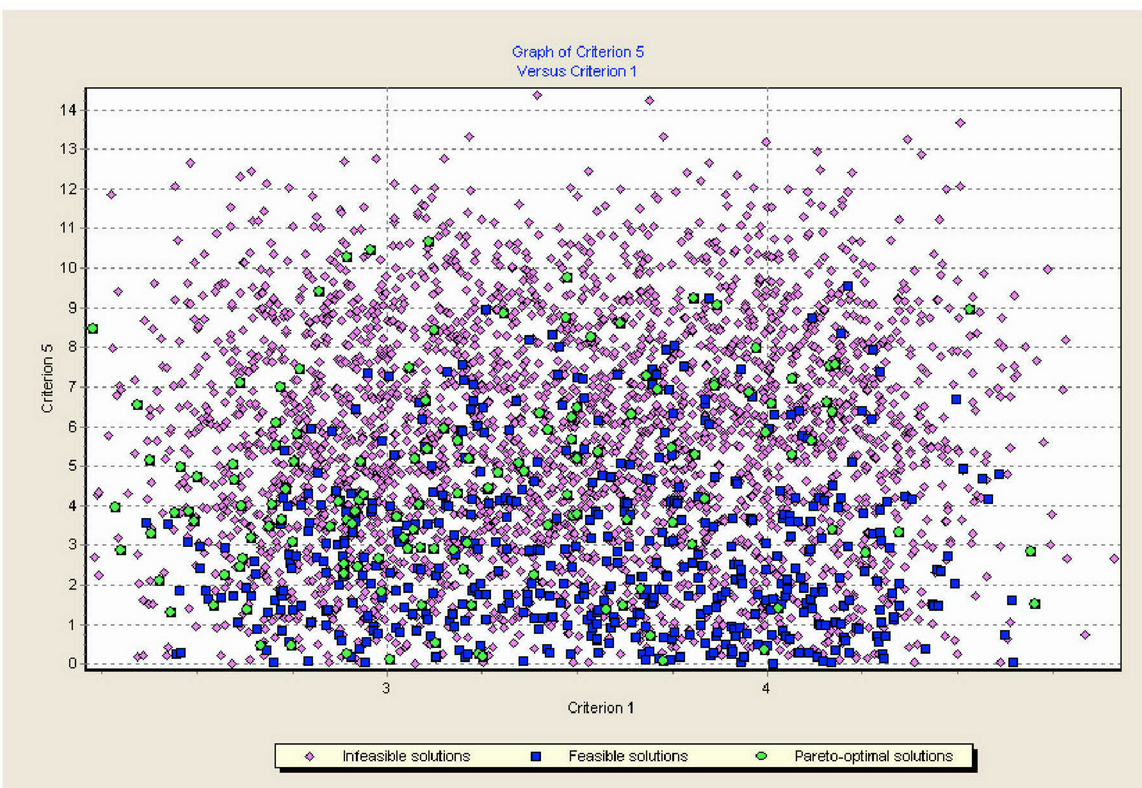

Figure 136 Criterion 1 (Minimized) vs. Criterion 5 (Maximized) – 6th Optimization.

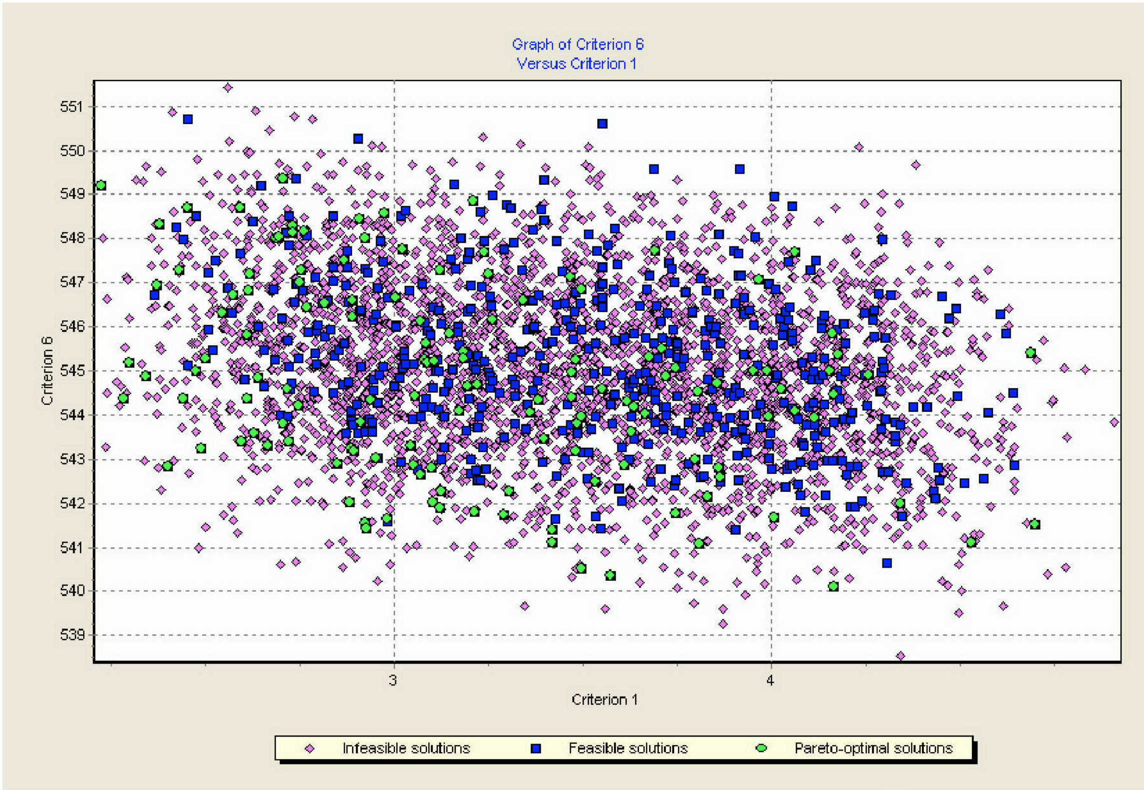

Figure 137 Criterion 1 (Minimized) vs. Criterion 6 (Minimized) – 6th Optimization.

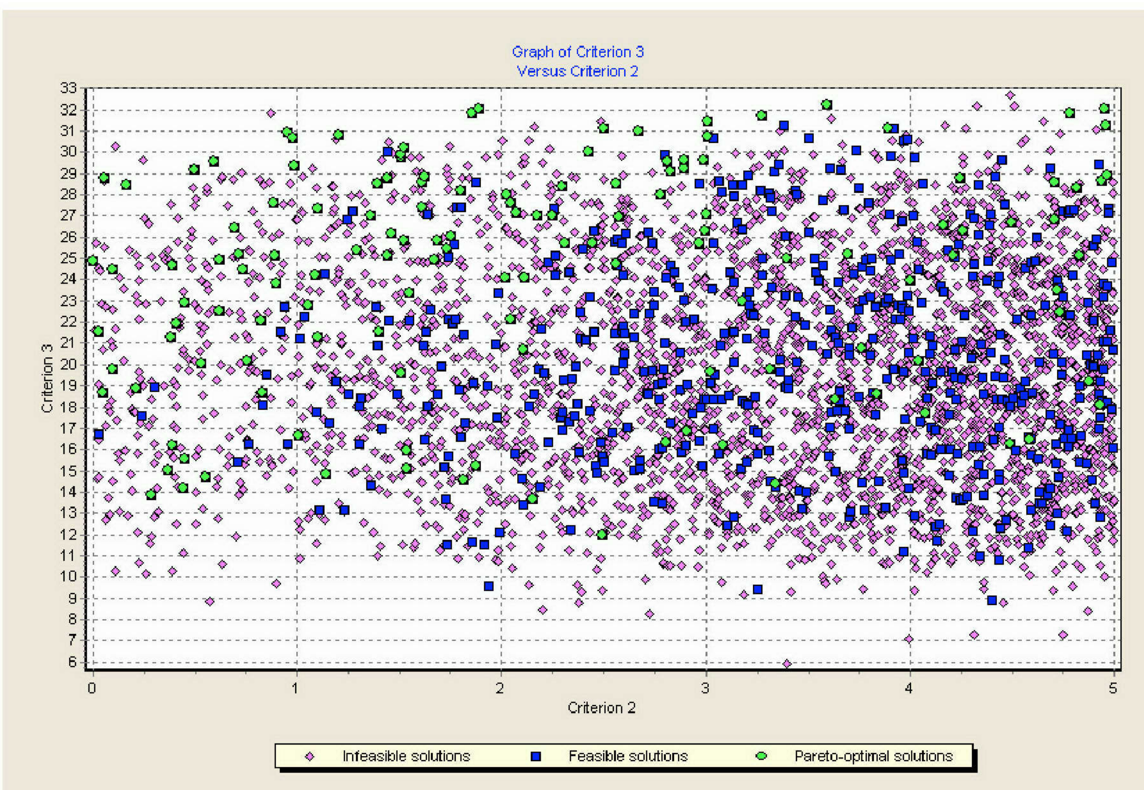

Figure 138 Criterion 2 (Minimized) vs. Criterion 3 (Maximized) – 6th Optimization.

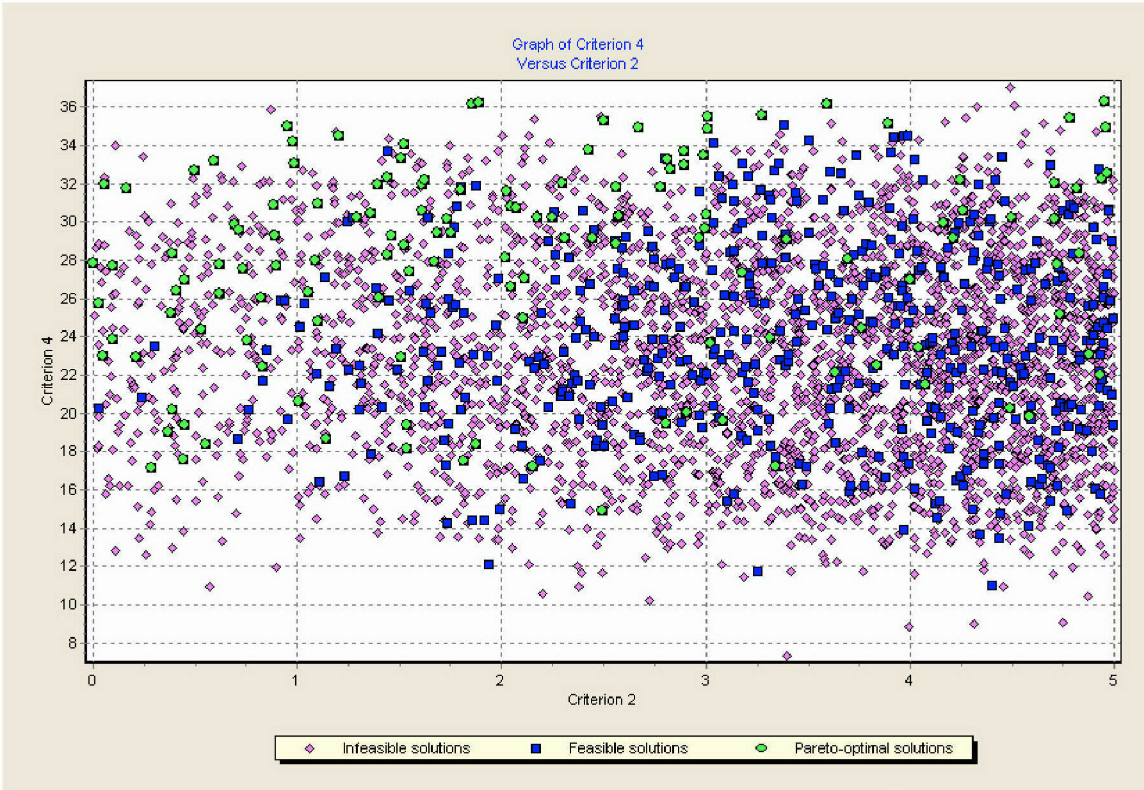

Figure 139 Criterion 2 (Minimized) vs. Criterion 4 (Maximized) – 6th Optimization.

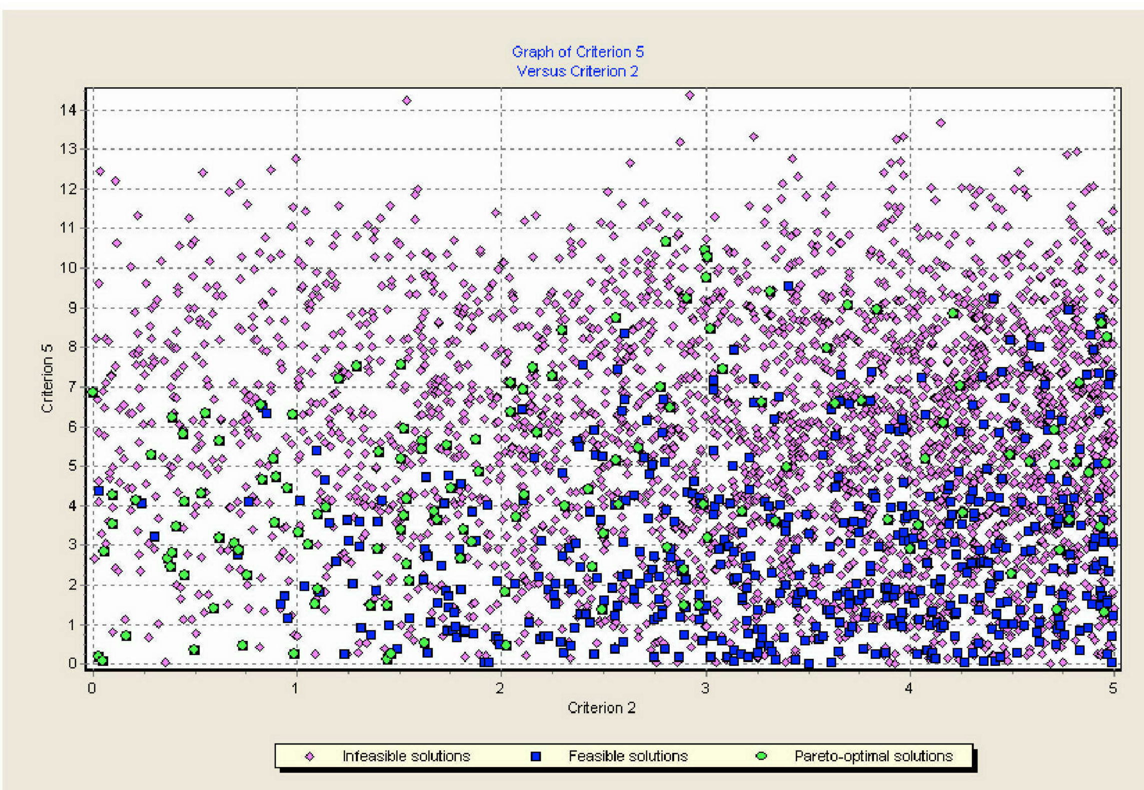

Figure 140 Criterion 2 (Minimized) vs. Criterion 5 (Maximized) – 6th Optimization.

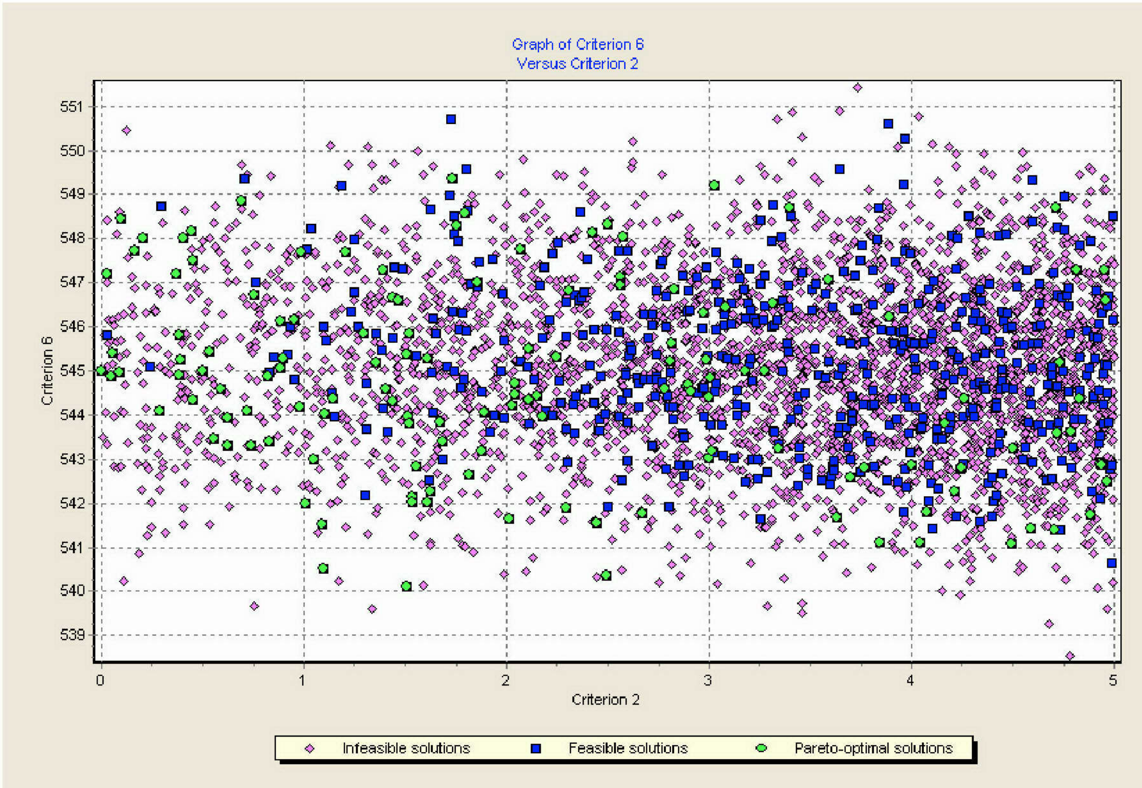

Figure 141 Criterion 2 (Minimized) vs. Criterion 6 (Minimized) – 6th Optimization.

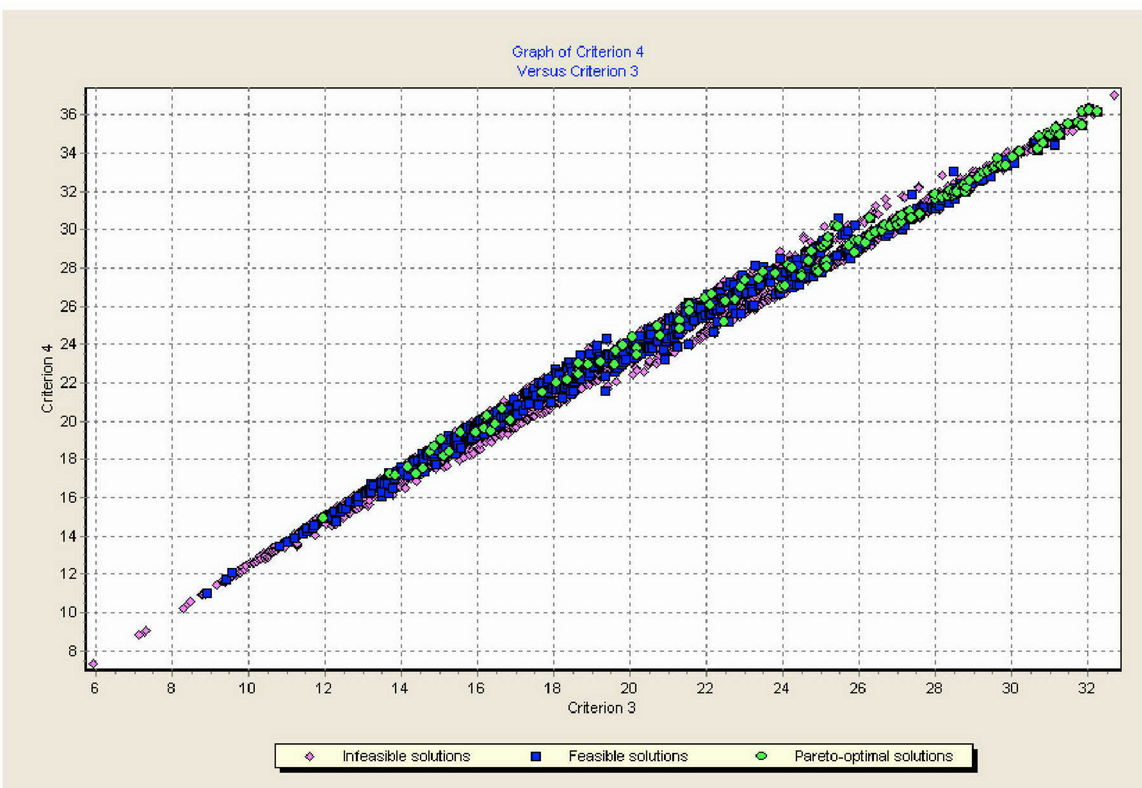

Figure 142 Criterion 3 (Maximized) vs. Criterion 4 (Maximized) – 6th Optimization.

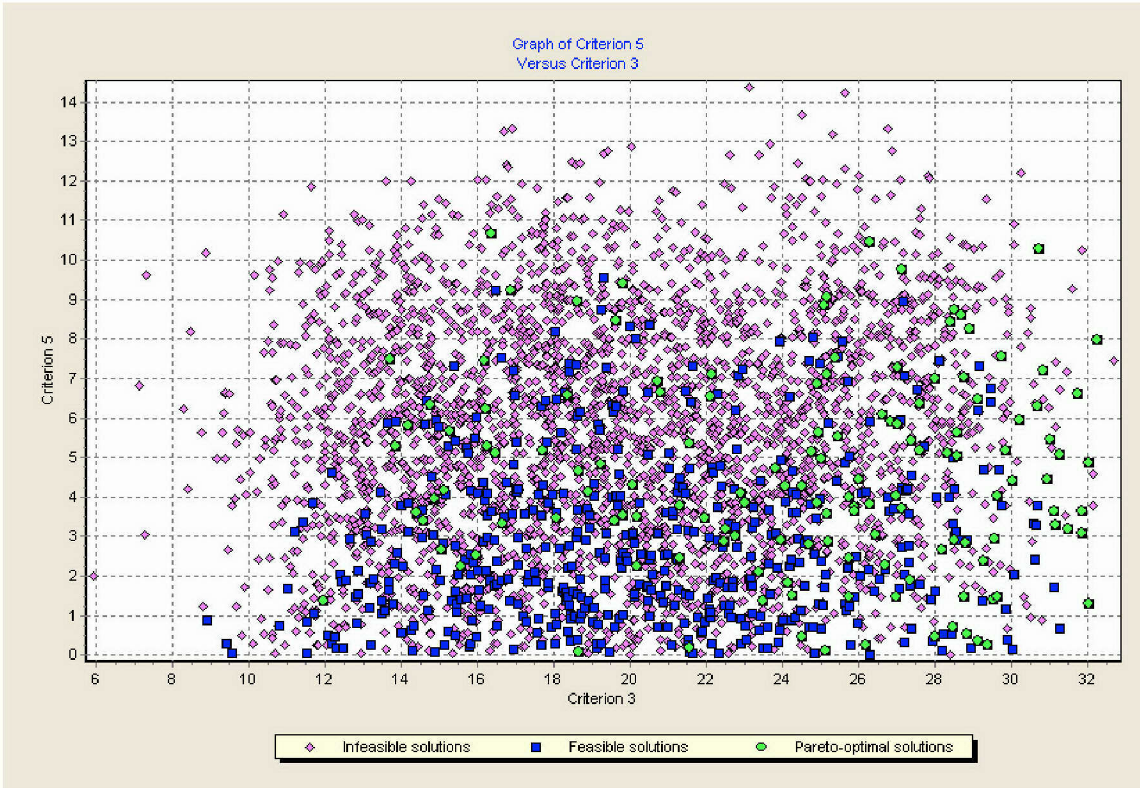

Figure 143 Criterion 3 (Maximized) vs. Criterion 5 (Maximized) – 6th Optimization.

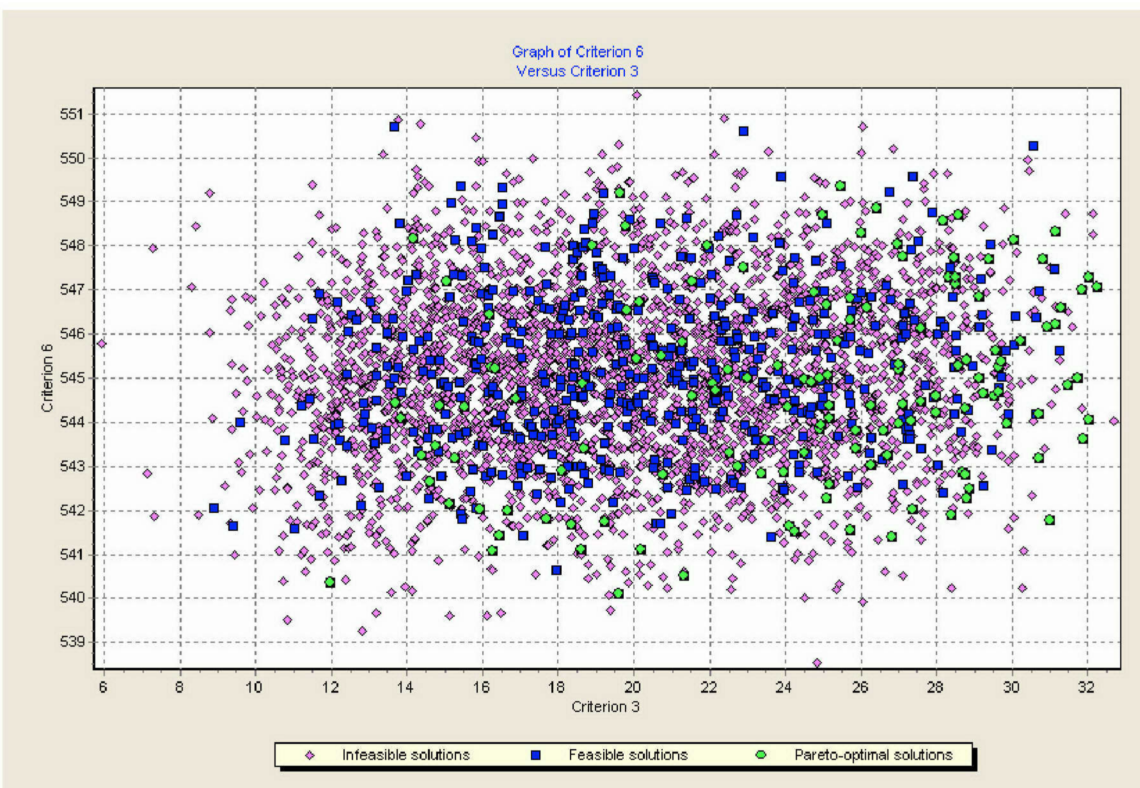

Figure 144 Criterion 3 (Maximized) vs. Criterion 6 (Minimized) – 6th Optimization.

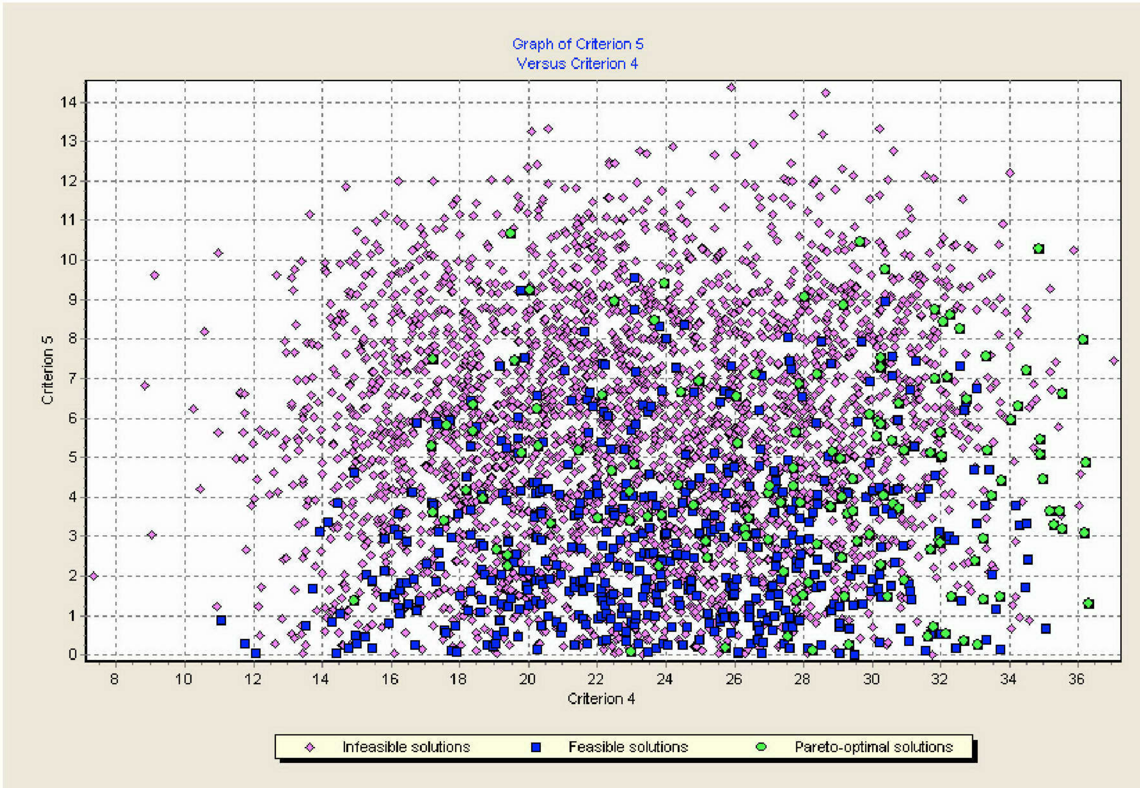

Figure 145 Criterion 4 (Maximized) vs. Criterion 5 (Maximized) – 6th Optimization.

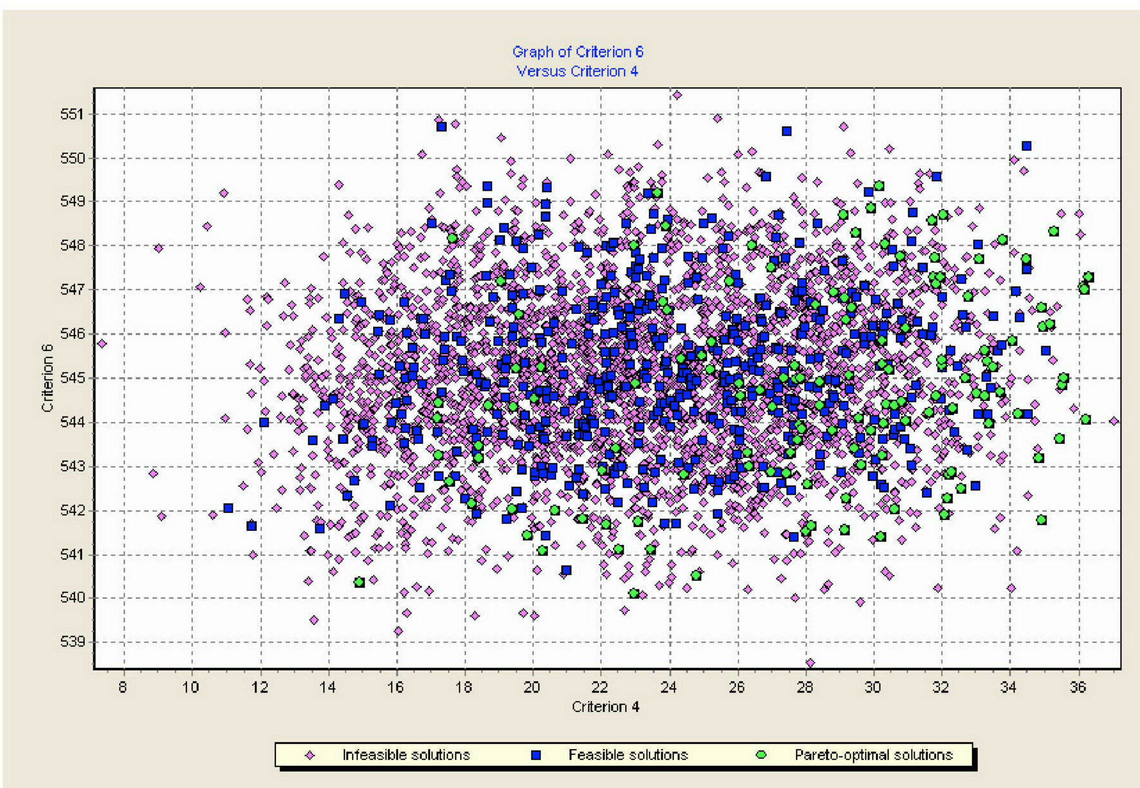

Figure 146 Criterion 4 (Maximized) vs. Criterion 6 (Minimized) – 6th Optimization.

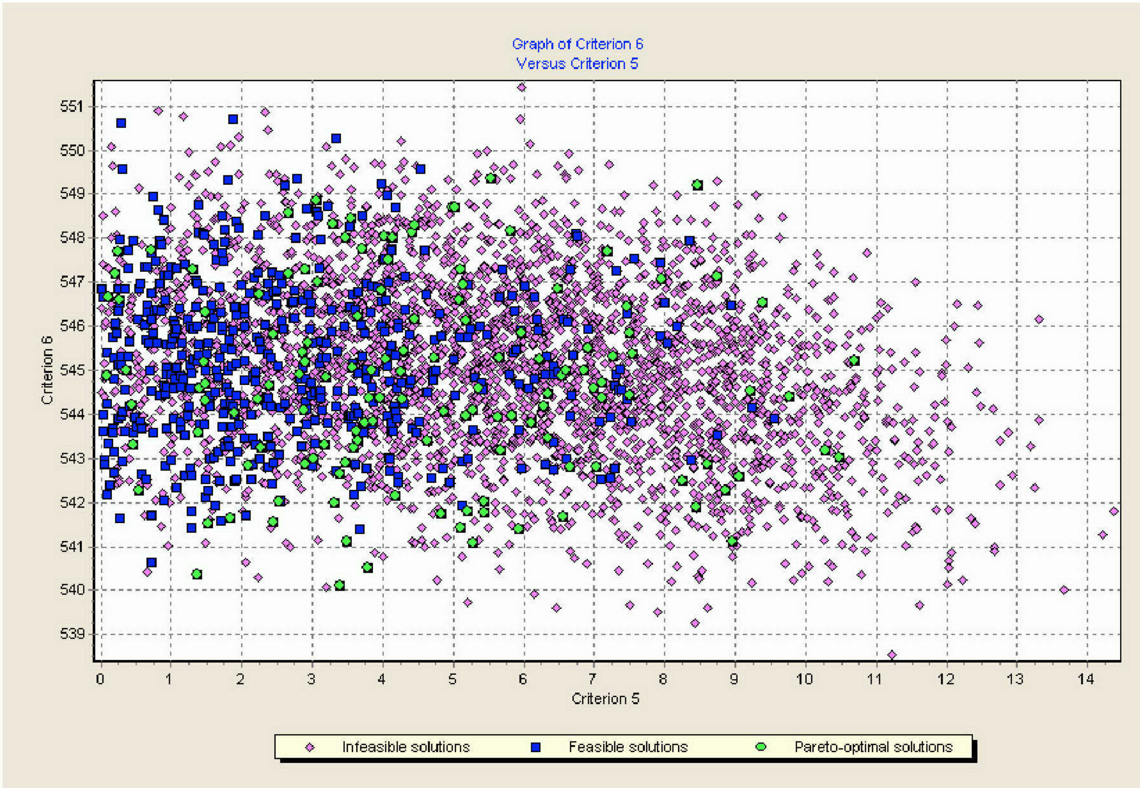

Figure 147 Criterion 5 (Maximized) vs. Criterion 6 (Minimized) – 6th Optimization.

APPENDIX M. DESIGN VARIABLE HISTOGRAMS (MIT MODEL)

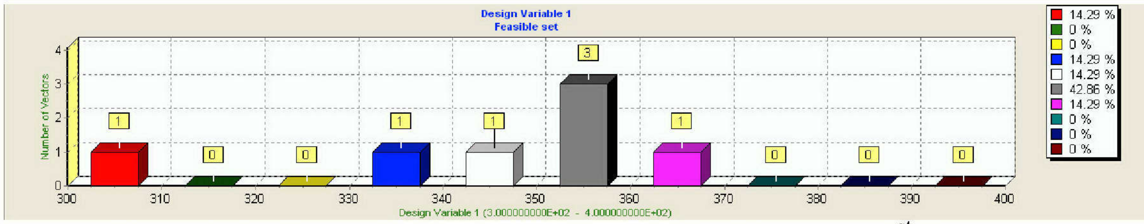

Figure 148 Design Var.1 – LWL, Feasible Set Histogram, 1st Opt.

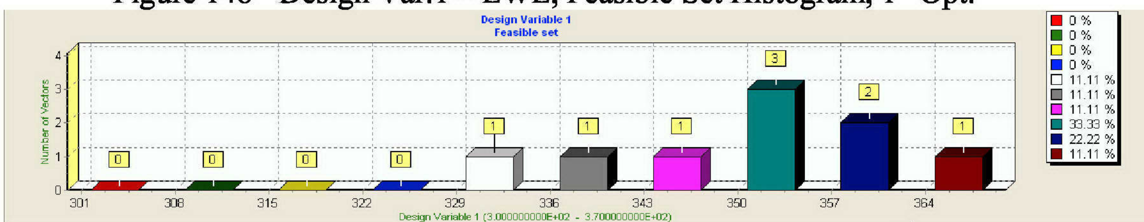

Figure 149 Design Var.1 – LWL, Feasible Set Histogram, 2nd Opt.

Figure 150 Design Var.1 – LWL, Feasible Set Histogram, 3rd Opt.

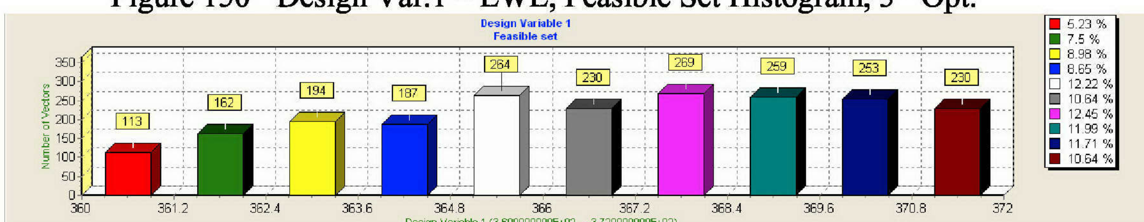

Figure 151 Design Var.1 – LWL, Feasible Set Histogram, 4th Opt.

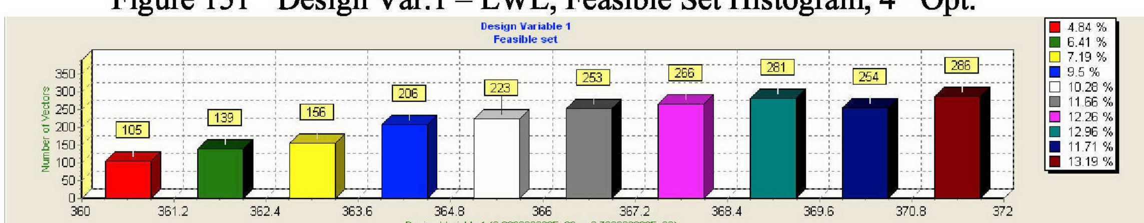

Figure 152 Design Var.1 – LWL, Feasible Set Histogram, 5th Opt.

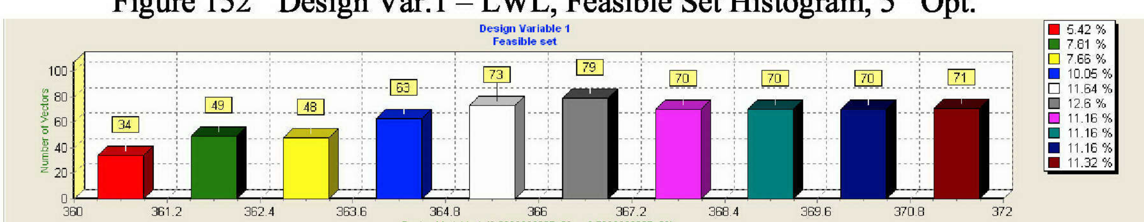

Figure 153 Design Var.1 – LWL, Feasible Set Histogram, 6th Opt.

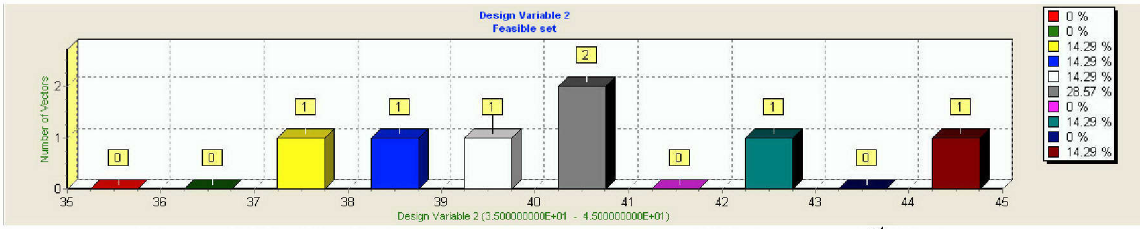

Figure 154 Design Var.2 – B, Feasible Set Histogram, 1st Opt.

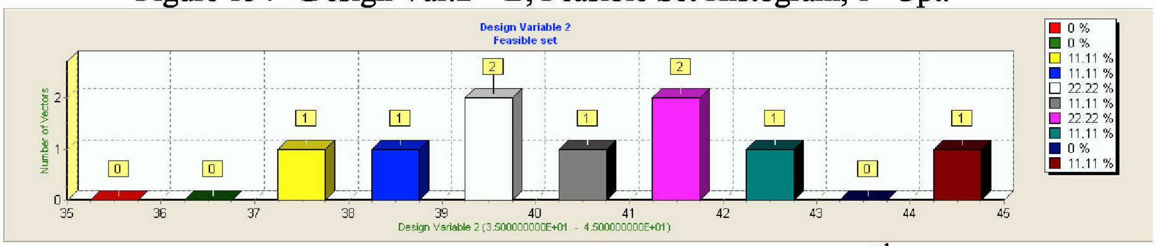

Figure 155 Design Var.2 – B, Feasible Set Histogram, 2nd Opt.

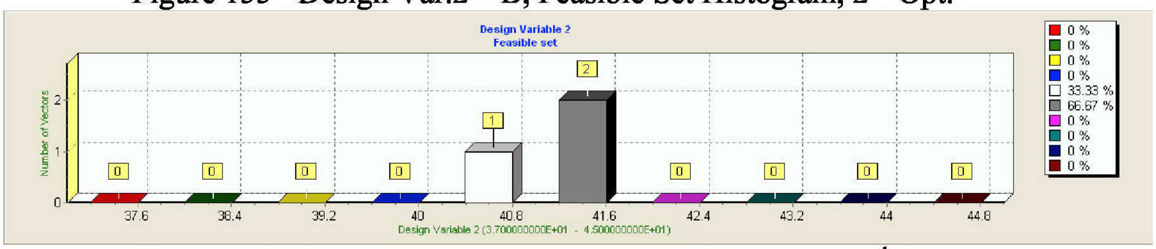

Figure 156 Design Var.2 – B, Feasible Set Histogram, 3rd Opt.

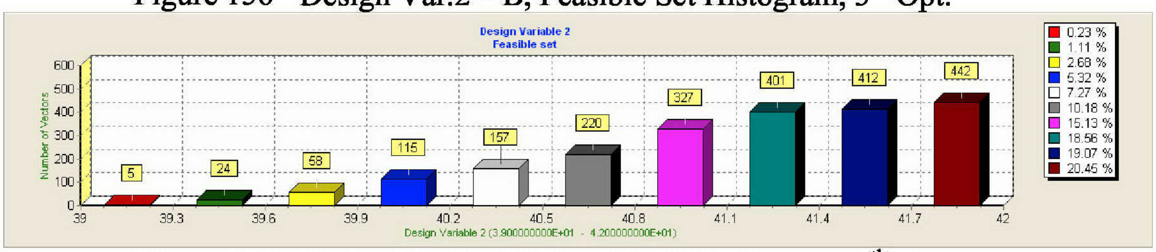

Figure 157 Design Var.2 – B, Feasible Set Histogram, 4th Opt.

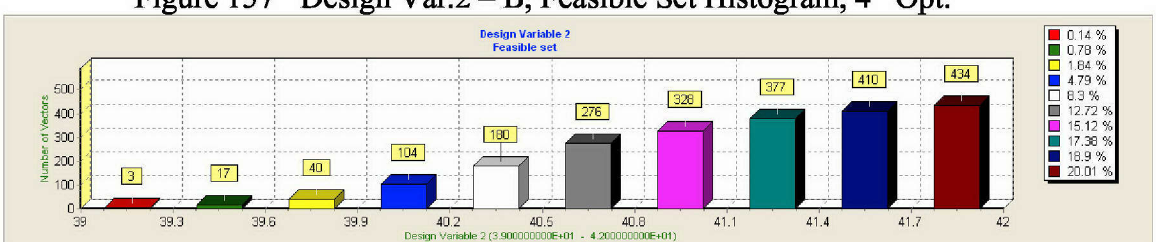

Figure 158 Design Var.2 – B, Feasible Set Histogram, 5th Opt.

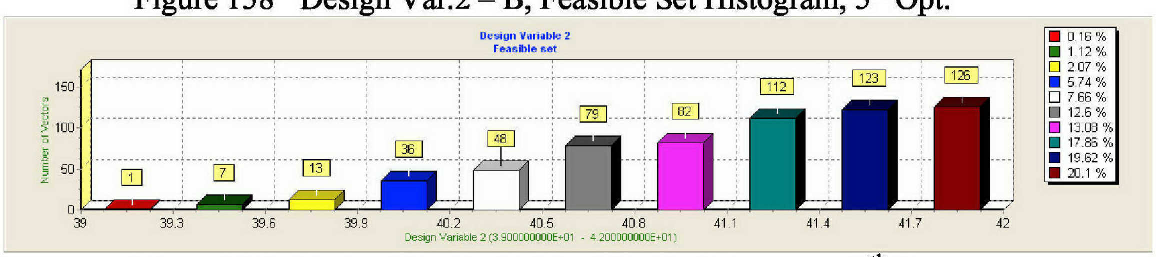

Figure 159 Design Var.2 – B, Feasible Set Histogram, 6th Opt.

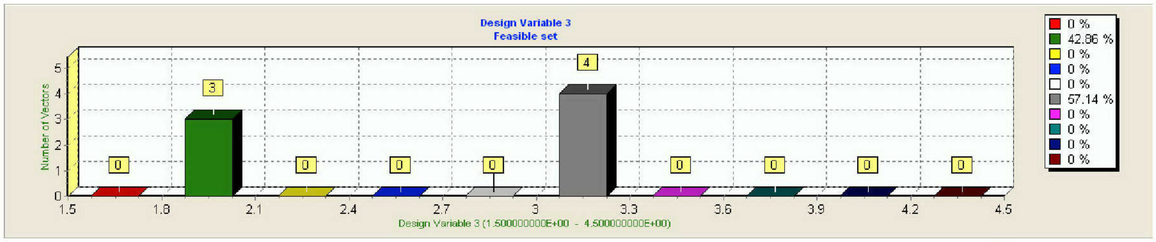

Figure 160 Design Var.3 – Ndecks, DISCRETE, Feasible Set Histogram, 1st Opt.

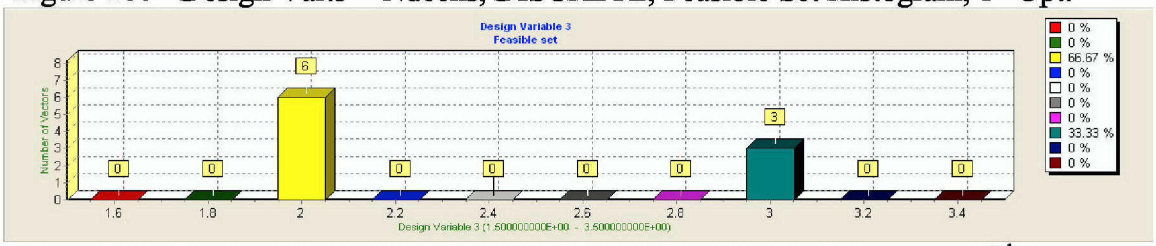

Figure 161 Design Var.3 – Ndecks, DISCRETE, Feasible Set Histogram, 2nd Opt.

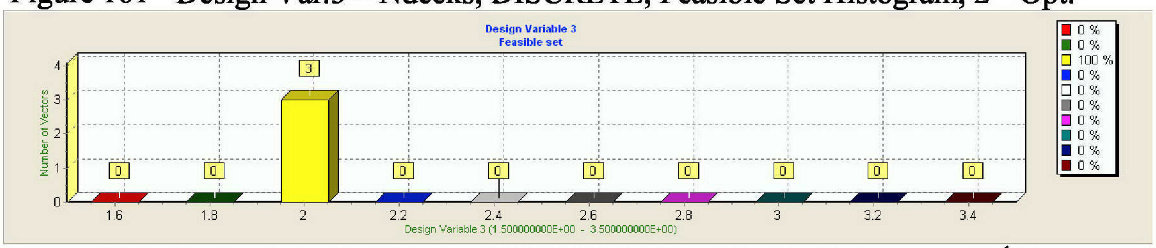

Figure 162 Design Var.3 – Ndecks, DISCRETE, Feasible Set Histogram, 3rd Opt.

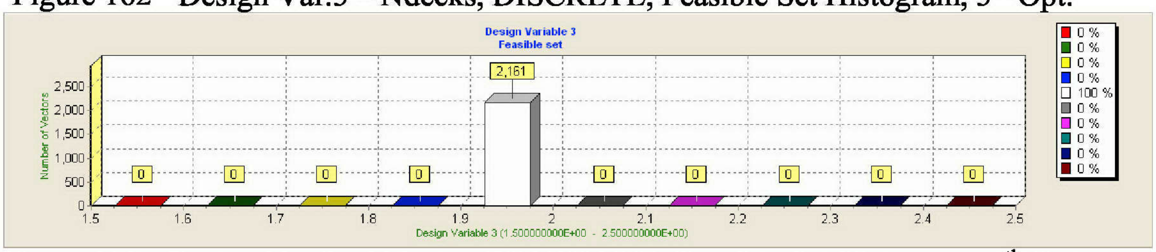

Figure 163 Design Var.3 – Ndecks, **CONSTANT**, Feasible Set Histogram, 4th Opt.

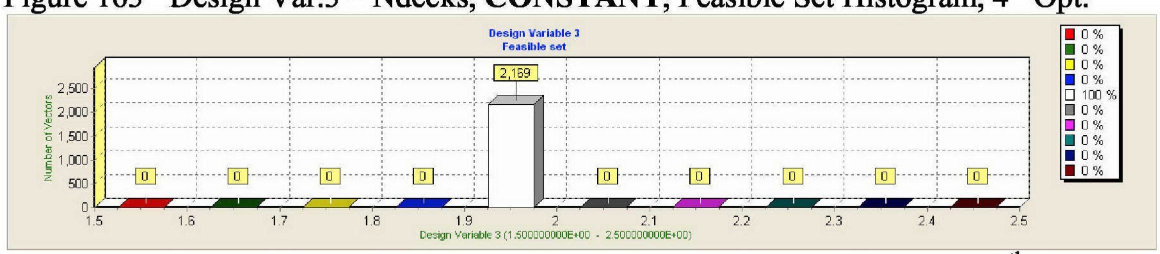

Figure 164 Design Var.3 – Ndecks, **CONSTANT**, Feasible Set Histogram, 5th Opt.

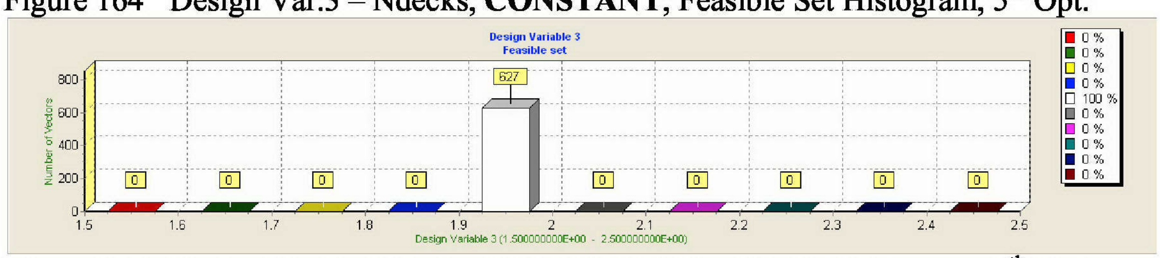

Figure 165 Design Var.3 – Ndecks, **CONSTANT**, Feasible Set Histogram, 6th Opt.

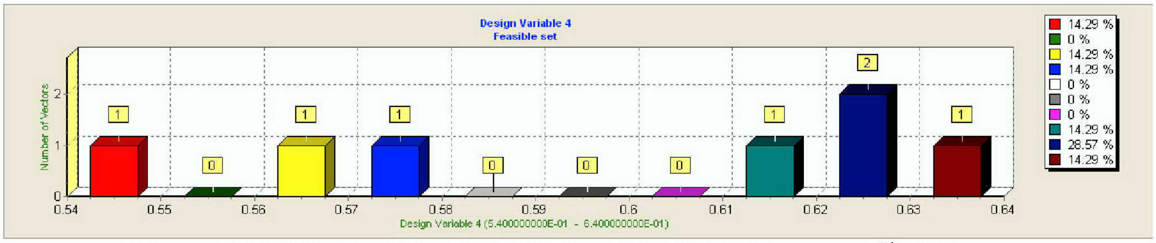

Figure 166 Design Var.4 – CP, Feasible Set Histogram, 1st Opt.

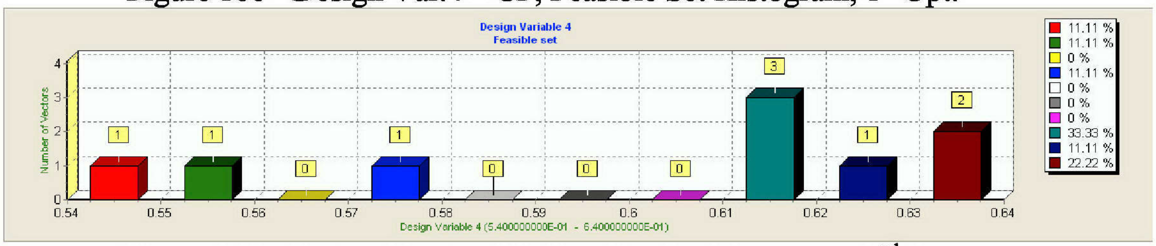

Figure 167 Design Var.4 – CP, Feasible Set Histogram, 2nd Opt.

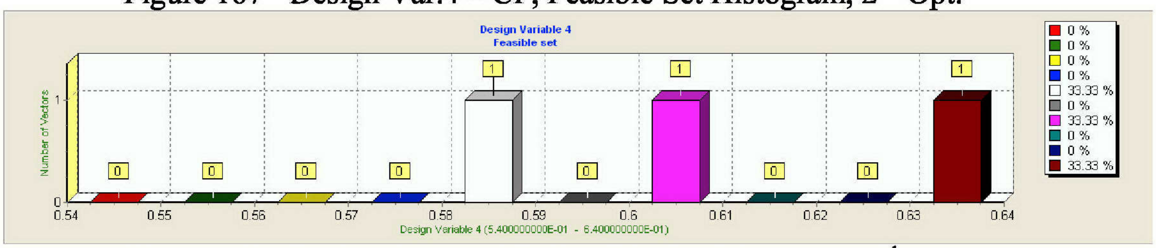

Figure 168 Design Var.4 – CP, Feasible Set Histogram, 3rd Opt.

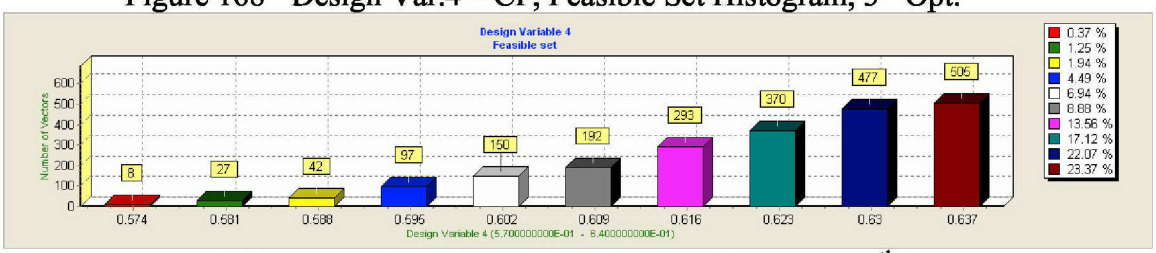

Figure 169 Design Var.4 – CP, Feasible Set Histogram, 4th Opt.

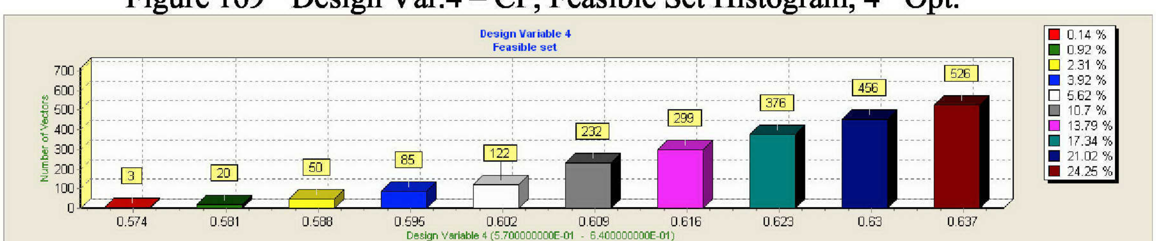

Figure 170 Design Var.4 – CP, Feasible Set Histogram, 5th Opt.

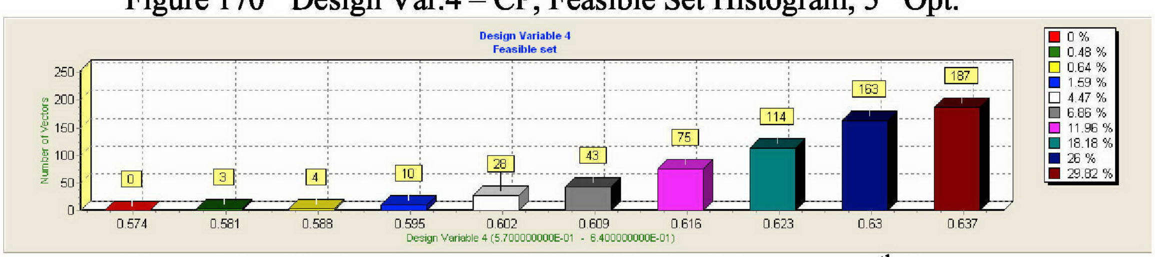

Figure 171 Design Var.4 – CP, Feasible Set Histogram, 6th Opt.

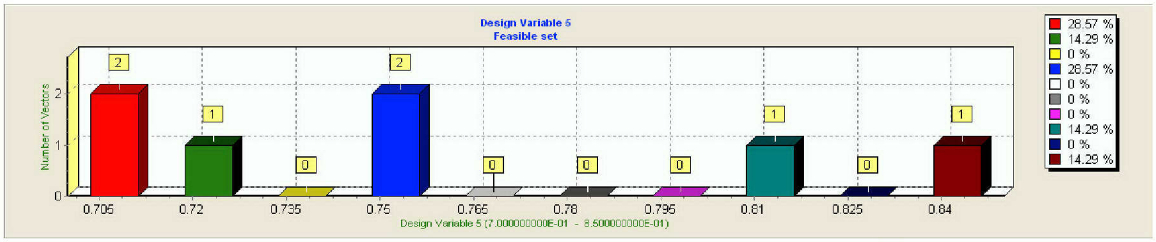

Figure 172 Design Var.5 – CX, Feasible Set Histogram, 1st Opt.

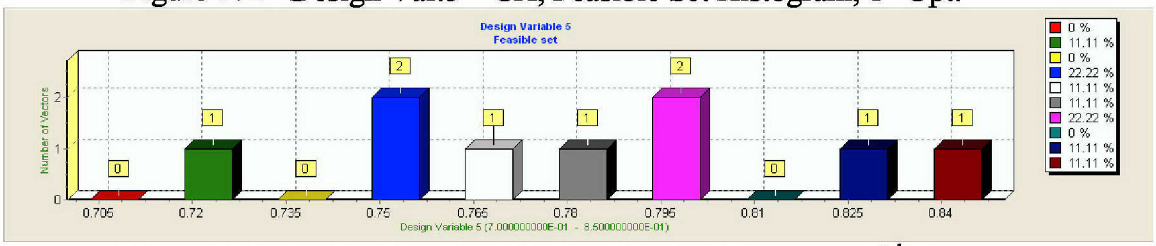

Figure 173 Design Var.5 – CX, Feasible Set Histogram, 2nd Opt.

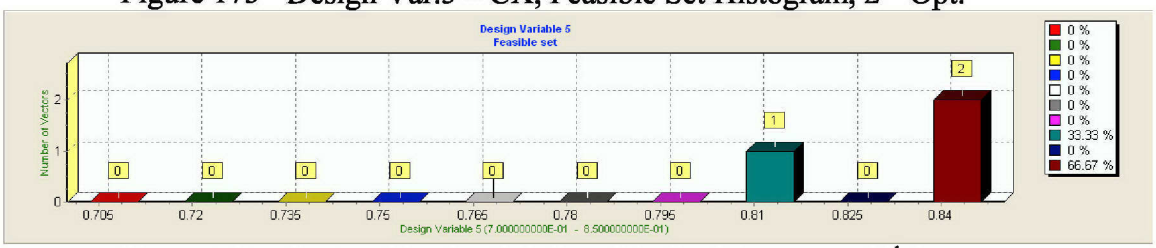

Figure 174 Design Var.5 – CX, Feasible Set Histogram, 3rd Opt.

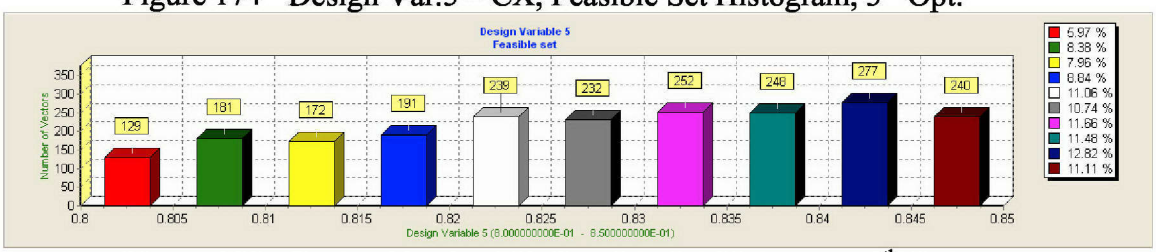

Figure 175 Design Var.5 – CX, Feasible Set Histogram, 4th Opt.

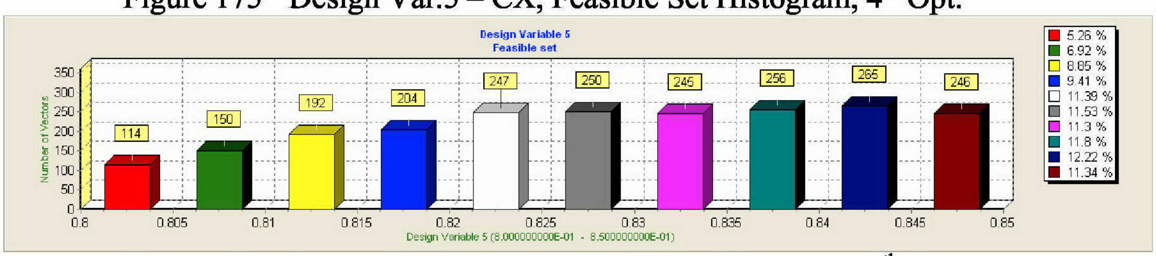

Figure 176 Design Var.5 – CX, Feasible Set Histogram, 5th Opt.

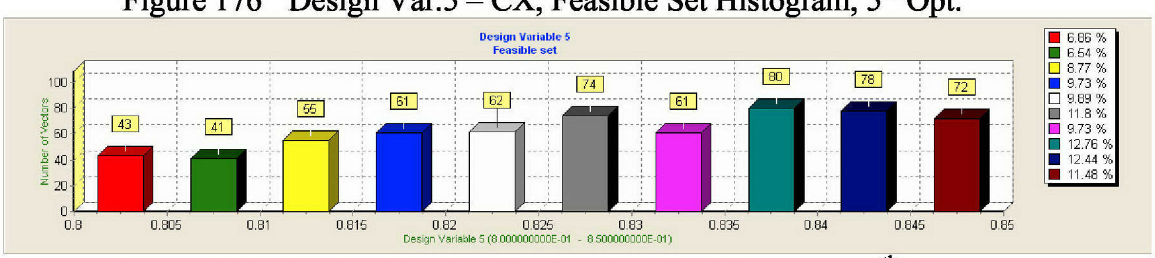

Figure 177 Design Var.5 – CX, Feasible Set Histogram, 6th Opt.

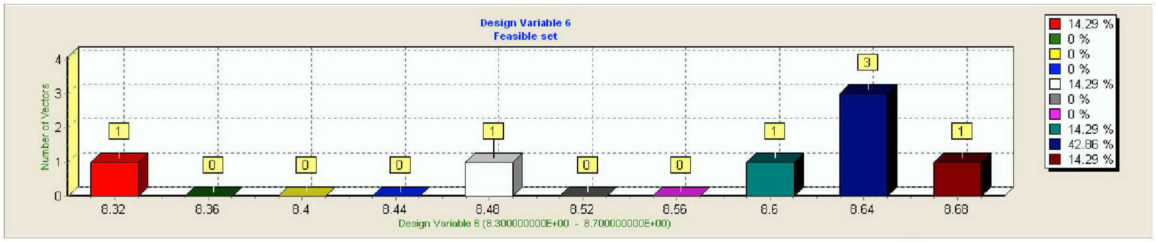

Figure 178 Design Var.6 – HDKh, Feasible Set Histogram, 1st Opt.

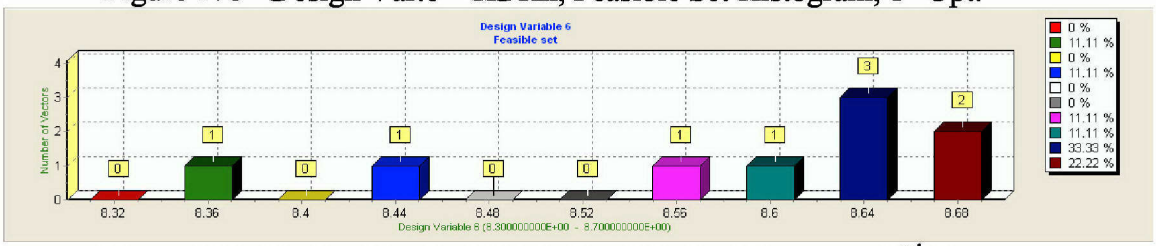

Figure 179 Design Var.6 – HDKh, Feasible Set Histogram, 2nd Opt.

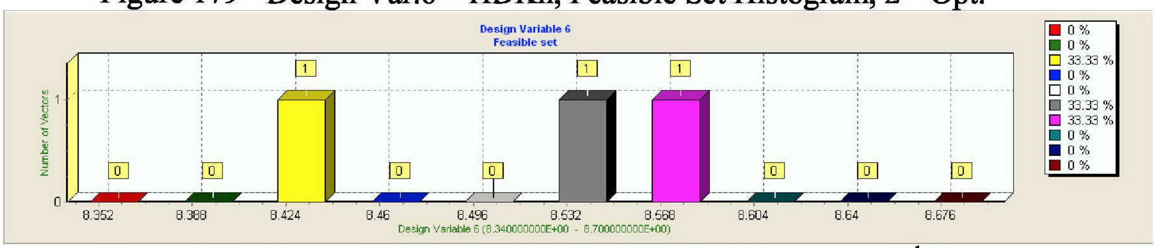

Figure 180 Design Var.6 – HDKh, Feasible Set Histogram, 3rd Opt.

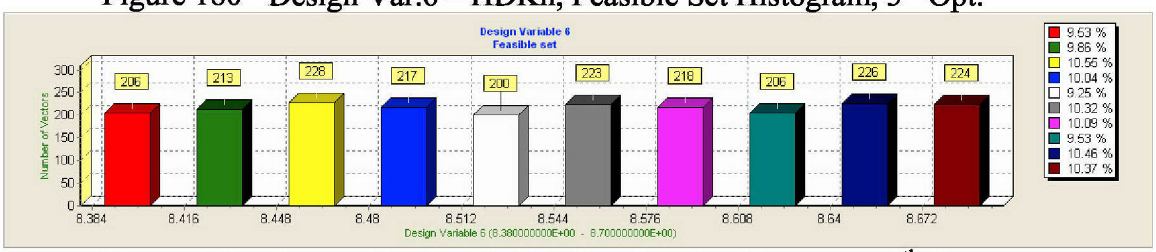

Figure 181 Design Var.6 – HDKh, Feasible Set Histogram, 4th Opt.

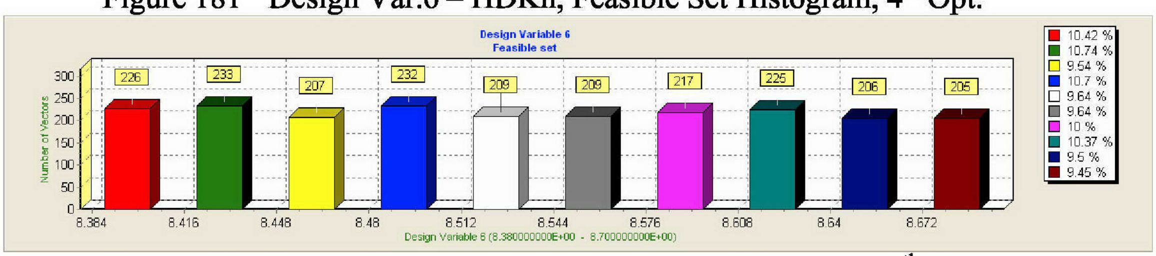

Figure 182 Design Var.6 – HDKh, Feasible Set Histogram, 5th Opt.

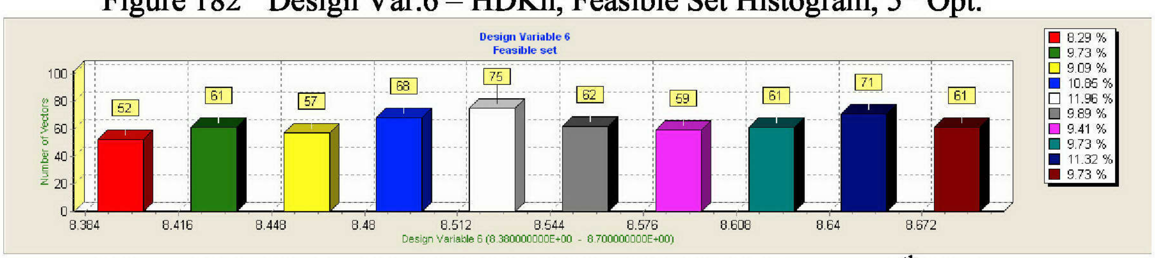

Figure 183 Design Var.6 – HDKh, Feasible Set Histogram, 6th Opt.

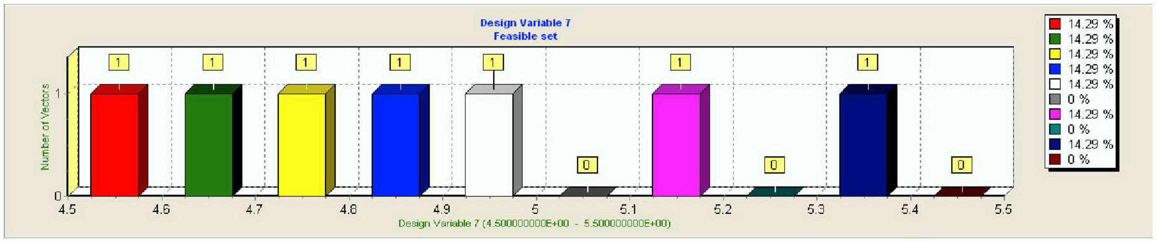

Figure 184 Design Var.7 – BILGE, Feasible Set Histogram, 1st Opt.

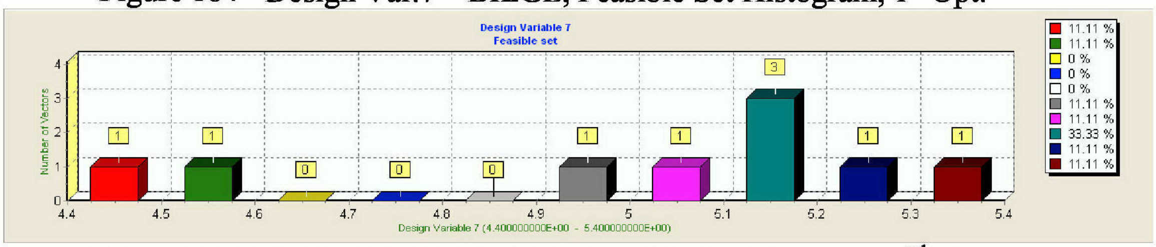

Figure 185 Design Var.7 – BILGE, Feasible Set Histogram, 2nd Opt.

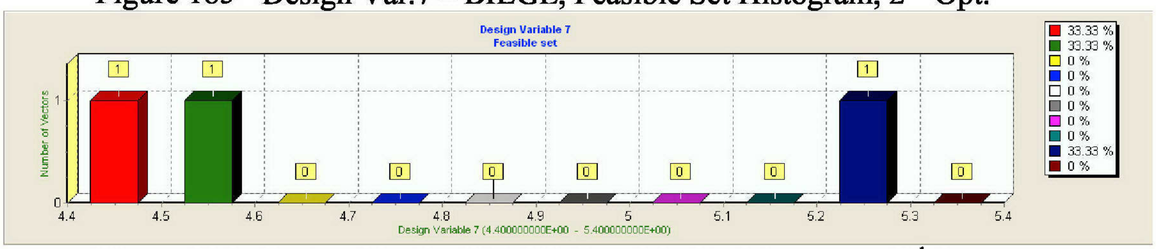

Figure 186 Design Var.7 – BILGE, Feasible Set Histogram, 3rd Opt.

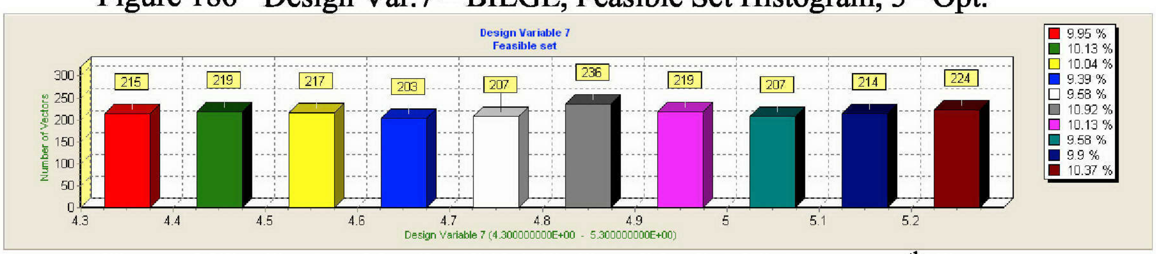

Figure 187 Design Var.7 – BILGE, Feasible Set Histogram, 4th Opt.

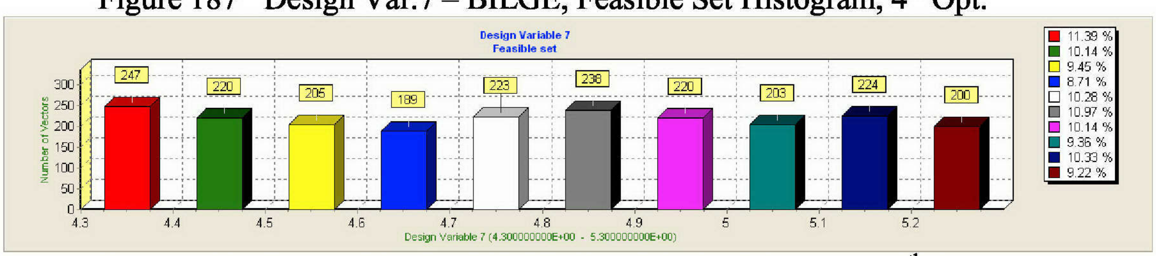

Figure 188 Design Var.7 – BILGE, Feasible Set Histogram, 5th Opt.

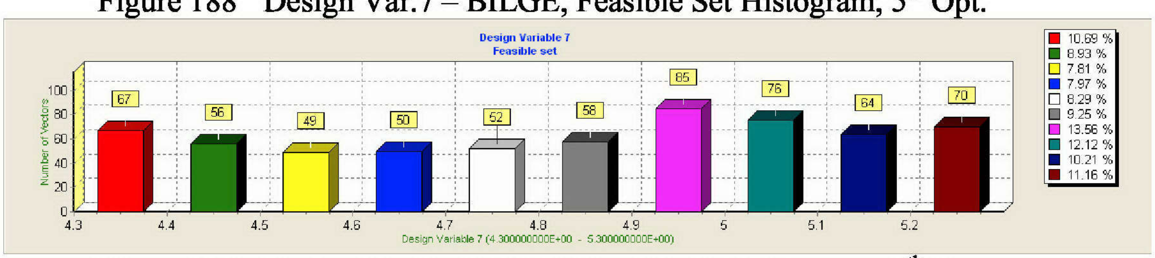

Figure 189 Design Var.7 – BILGE, Feasible Set Histogram, 6th Opt.

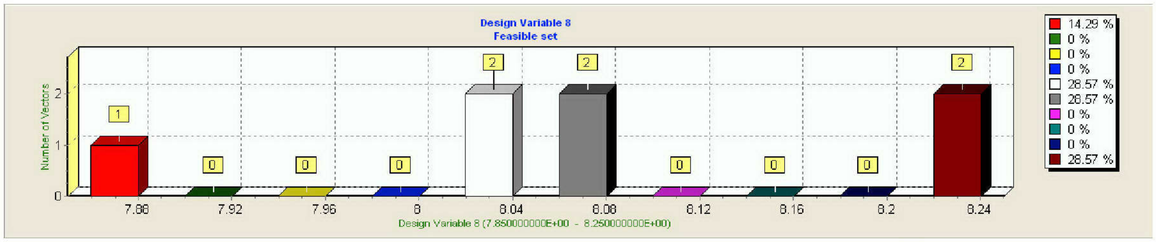

Figure 190 Design Var.8 – HDKd, Feasible Set Histogram, 1st Opt.

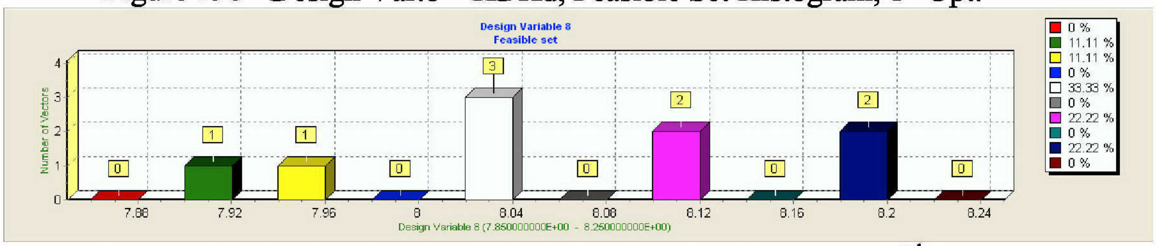

Figure 191 Design Var.8 – HDKd, Feasible Set Histogram, 2nd Opt.

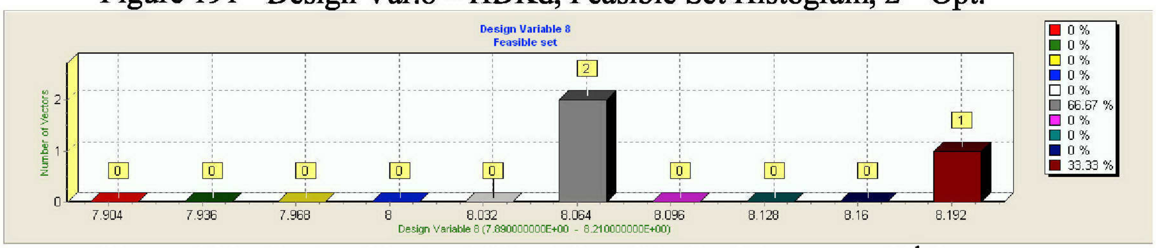

Figure 192 Design Var.8 – HDKd, Feasible Set Histogram, 3rd Opt.

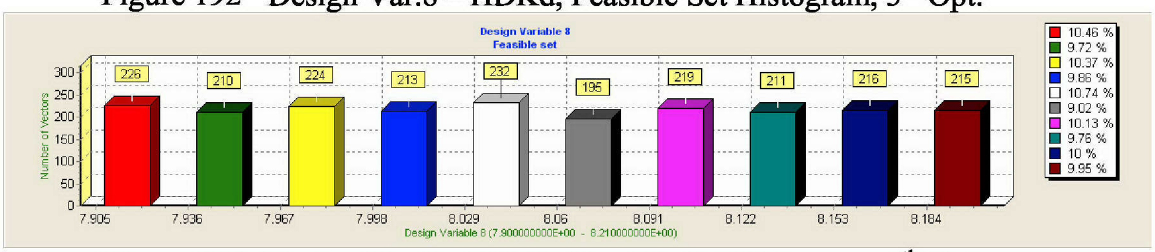

Figure 193 Design Var.8 – HDKd, Feasible Set Histogram, 4th Opt.

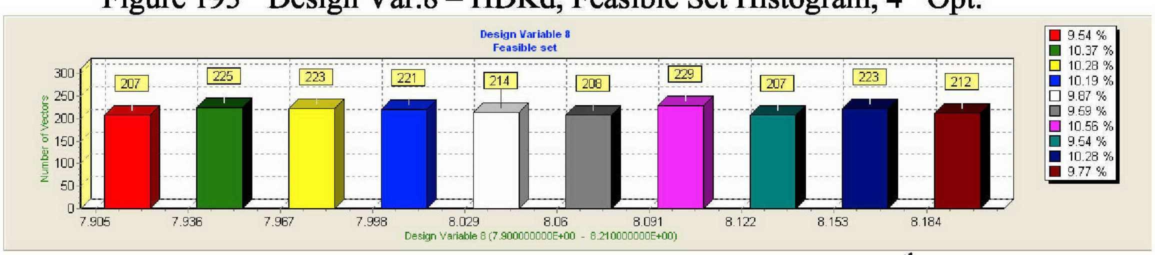

Figure 194 Design Var.8 – HDKd, Feasible Set Histogram, 5th Opt.

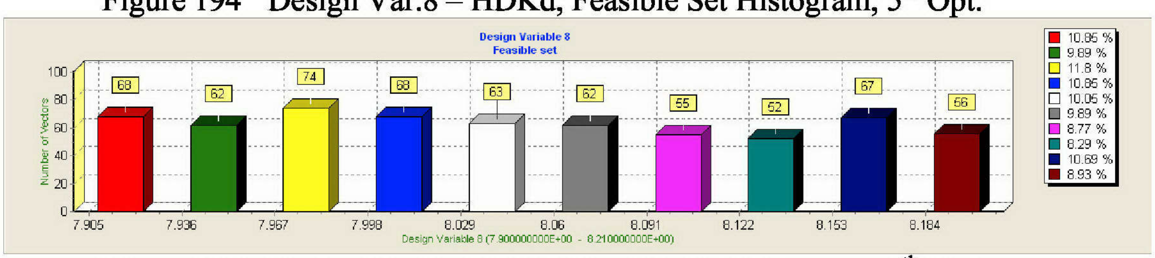

Figure 195 Design Var.8 – HDKd, Feasible Set Histogram, 6th Opt.

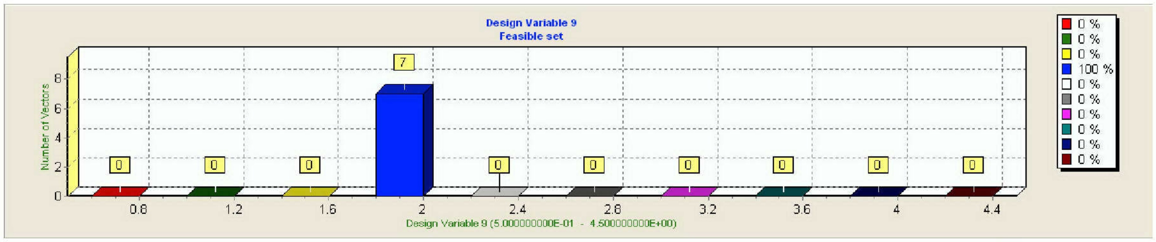

Figure 196 Design Var.9 – NPENG, DISCRETE, Feasible Set Histogram, 1st Opt.

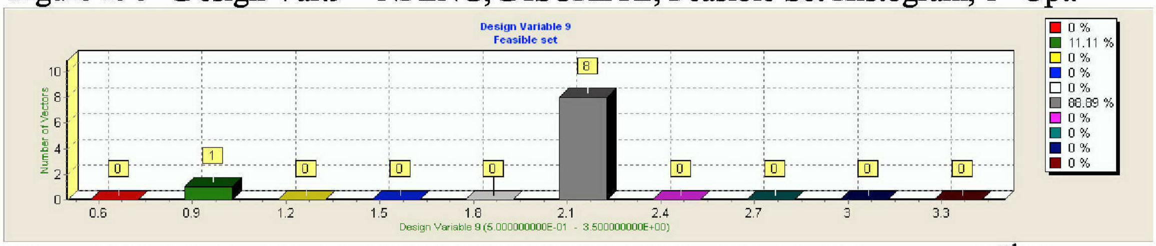

Figure 197 Design Var.9 – NPENG, DISCRETE, Feasible Set Histogram, 2nd Opt.

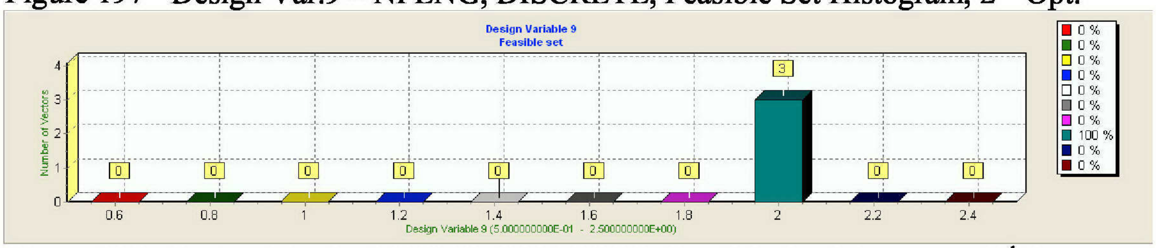

Figure 198 Design Var.9 – NPENG, DISCRETE, Feasible Set Histogram, 3rd Opt.

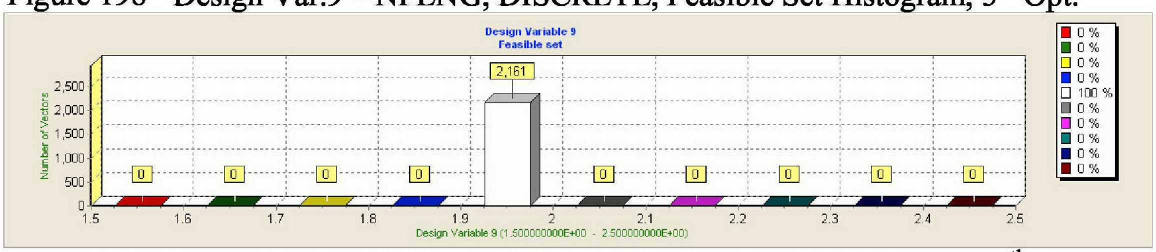

Figure 199 Design Var.9 – NPENG, **CONSTANT**, Feasible Set Histogram, 4th Opt.

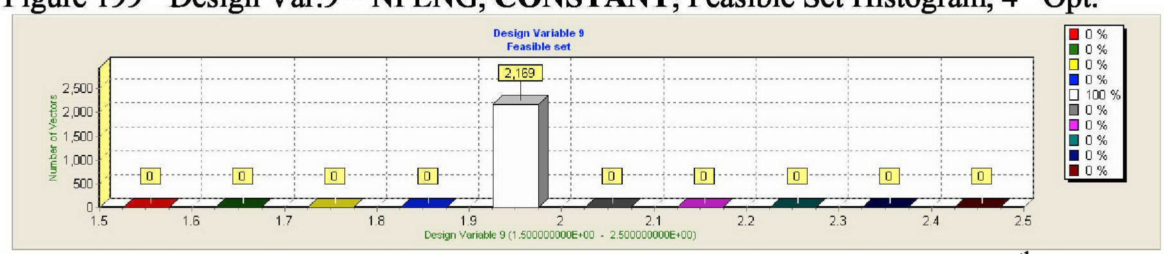

Figure 200 Design Var.9 – NPENG, **CONSTANT**, Feasible Set Histogram, 5th Opt.

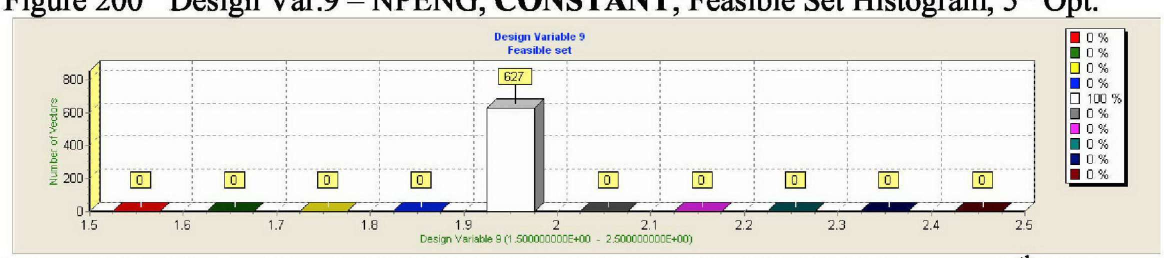

Figure 201 Design Var.9 – NPENG, **CONSTANT**, Feasible Set Histogram, 6th Opt.

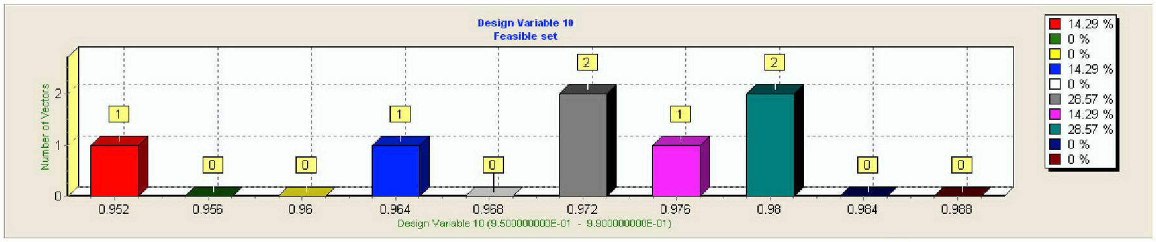

Figure 202 Design Var.10 – eta, Feasible Set Histogram, 1st Opt.

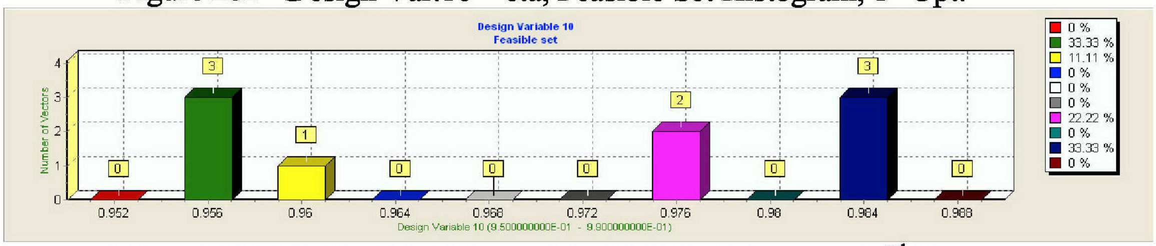

Figure 203 Design Var.10 – eta, Feasible Set Histogram, 2nd Opt.

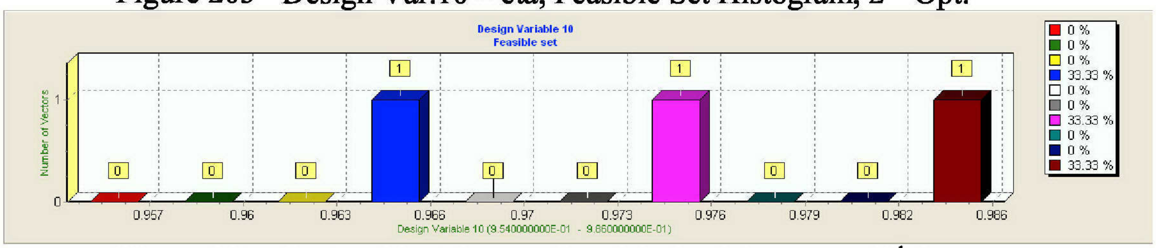

Figure 204 Design Var.10 – eta, Feasible Set Histogram, 3rd Opt.

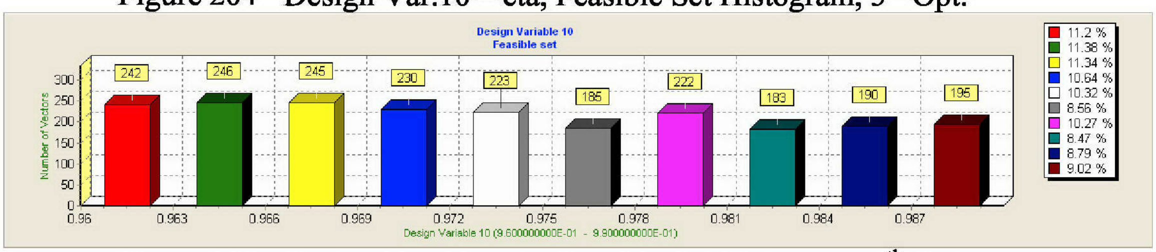

Figure 205 Design Var.10 – eta, Feasible Set Histogram, 4th Opt.

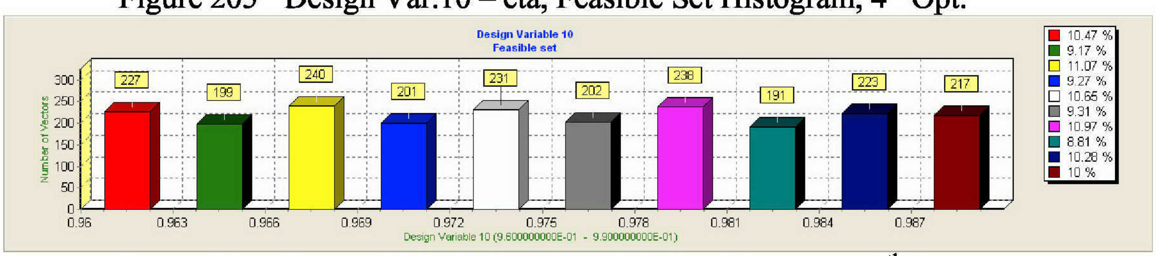

Figure 206 Design Var.10 – eta, Feasible Set Histogram, 5th Opt.

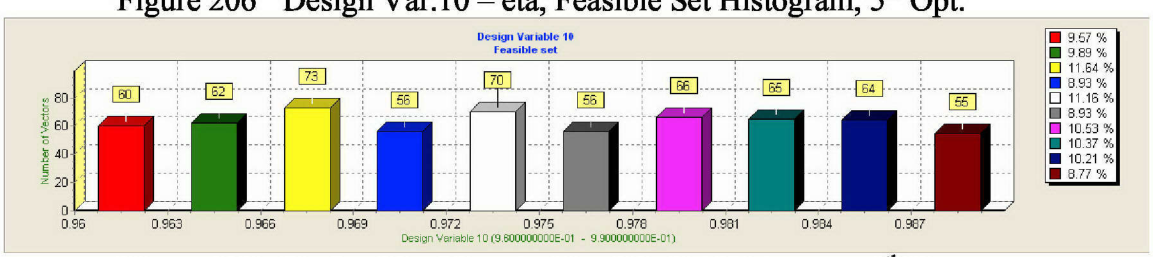

Figure 207 Design Var.10 – eta, Feasible Set Histogram, 6th Opt.

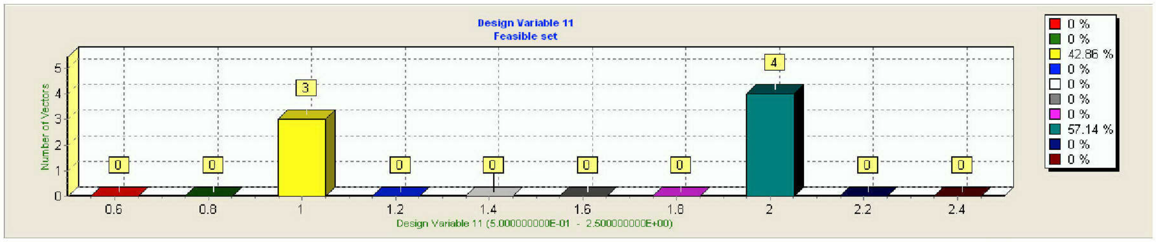

Figure 208 Design Var.11 – NDIE, DISCRETE, Feasible Set Histogram, 1st Opt.

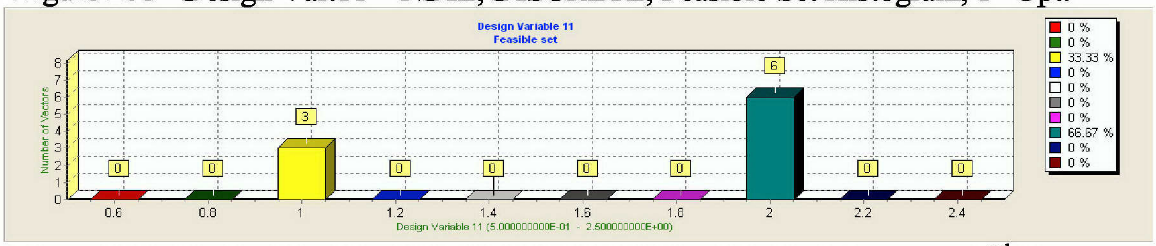

Figure 209 Design Var.11 – NDIE, DISCRETE, Feasible Set Histogram, 2nd Opt.

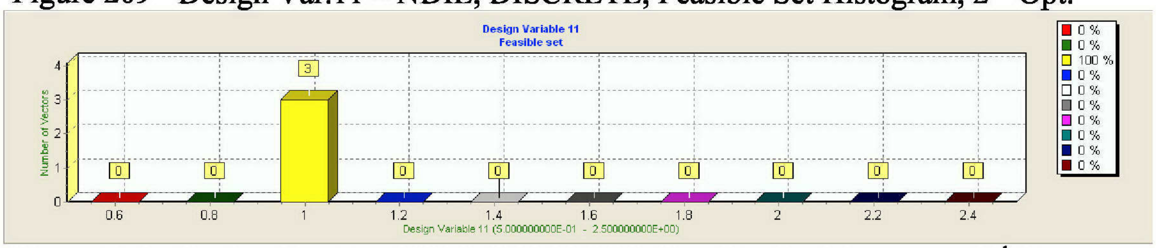

Figure 210 Design Var.11 – NDIE, DISCRETE, Feasible Set Histogram, 3rd Opt.

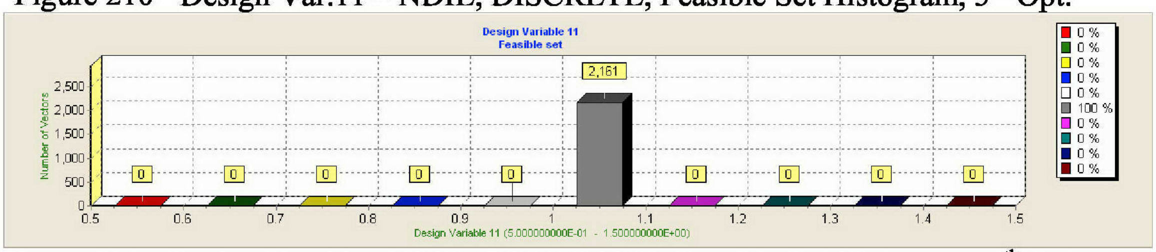

Figure 211 Design Var.11 – NDIE, **CONSTANT**, Feasible Set Histogram, 4th Opt.

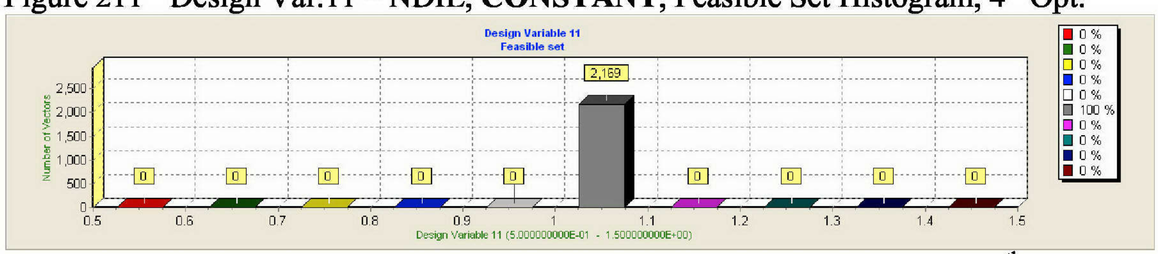

Figure 212 Design Var.11 – NDIE, **CONSTANT**, Feasible Set Histogram, 5th Opt.

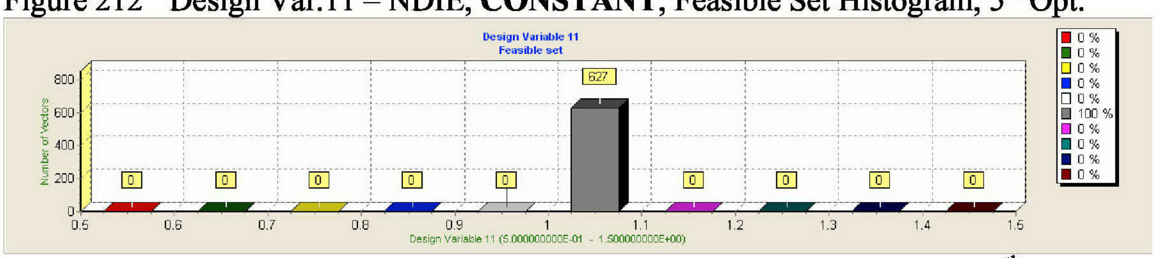

Figure 213 Design Var.11 – NDIE, **CONSTANT**, Feasible Set Histogram, 6th Opt.

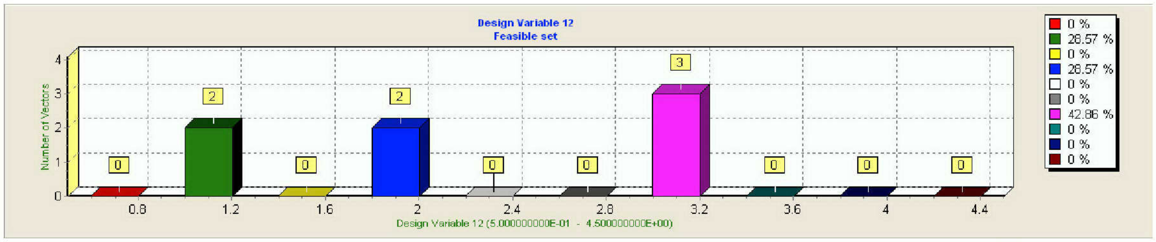

Figure 214 Design Var.12 – NHPIE, DISCRETE, Feasible Set Histogram, 1st Opt.

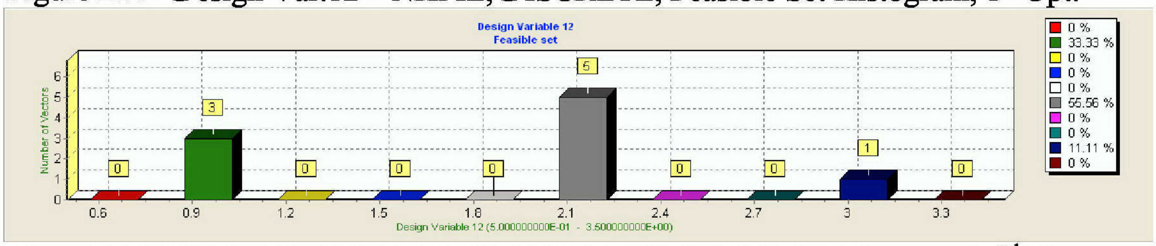

Figure 215 Design Var.12 – NHPIE, DISCRETE, Feasible Set Histogram, 2nd Opt.

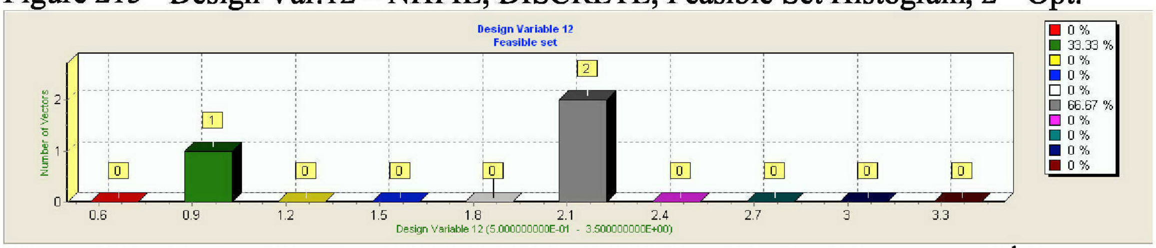

Figure 216 Design Var.12 – NHPIE, DISCRETE, Feasible Set Histogram, 3rd Opt.

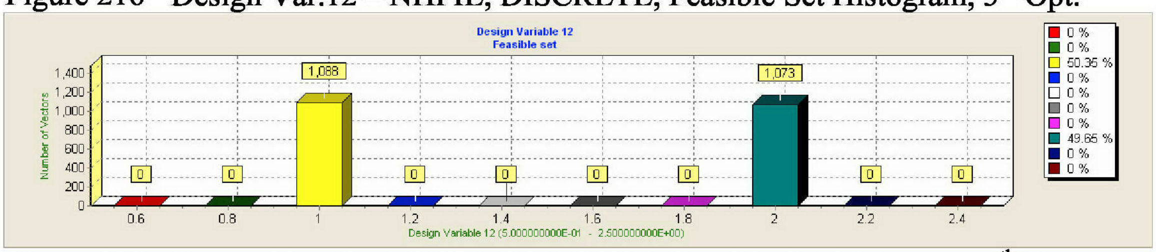

Figure 217 Design Var.12 – NHPIE, DISCRETE, Feasible Set Histogram, 4th Opt.

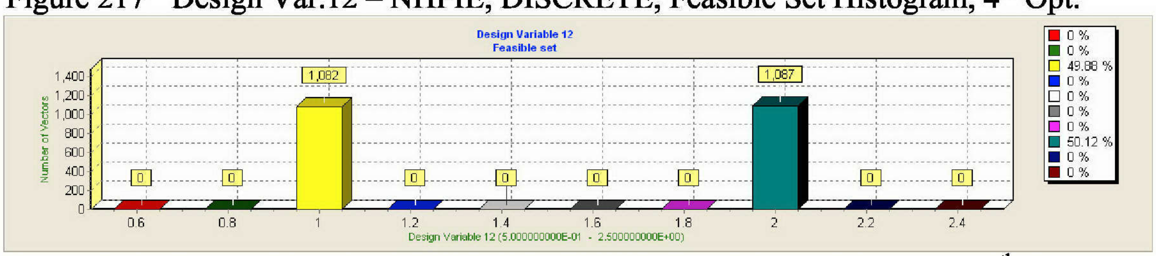

Figure 218 Design Var.12 – NHPIE, DISCRETE, Feasible Set Histogram, 5th Opt.

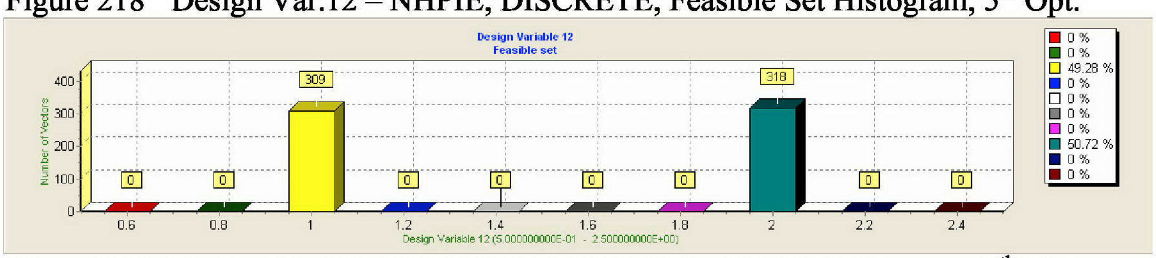

Figure 219 Design Var.12 – NHPIE, DISCRETE, Feasible Set Histogram, 6th Opt.

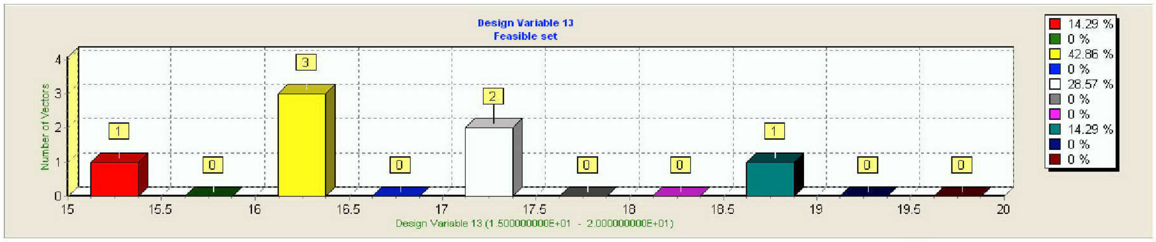

Figure 220 Design Var.13 – WF46, Feasible Set Histogram, 1st Opt.

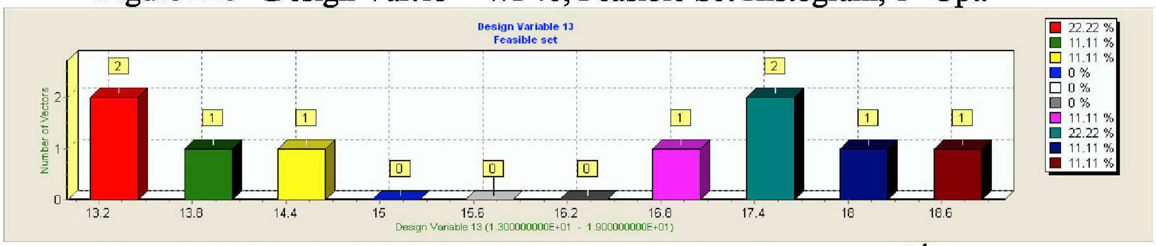

Figure 221 Design Var.13 – WF46, Feasible Set Histogram, 2nd Opt.

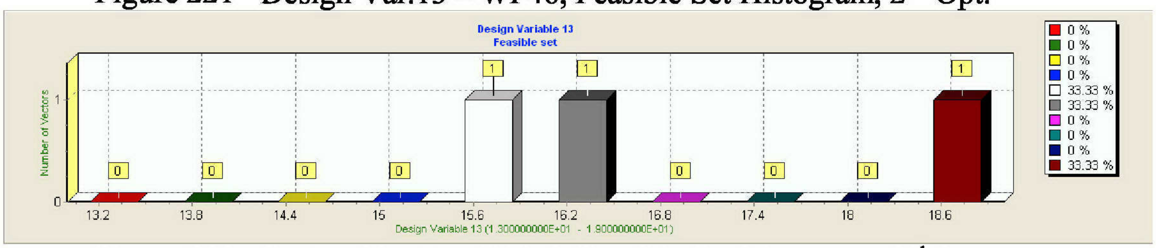

Figure 222 Design Var.13 – WF46, Feasible Set Histogram, 3rd Opt.

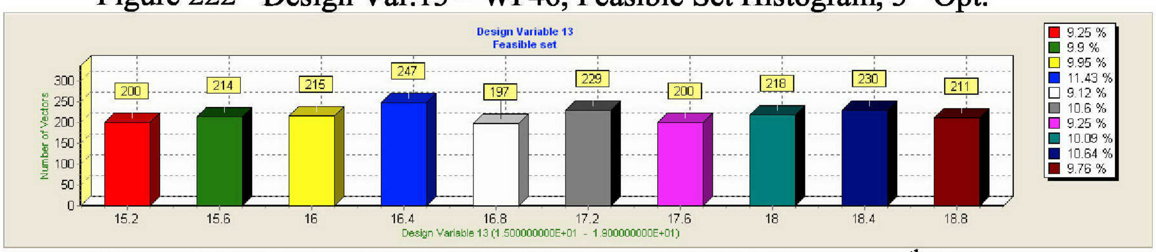

Figure 223 Design Var.13 – WF46, Feasible Set Histogram, 4th Opt.

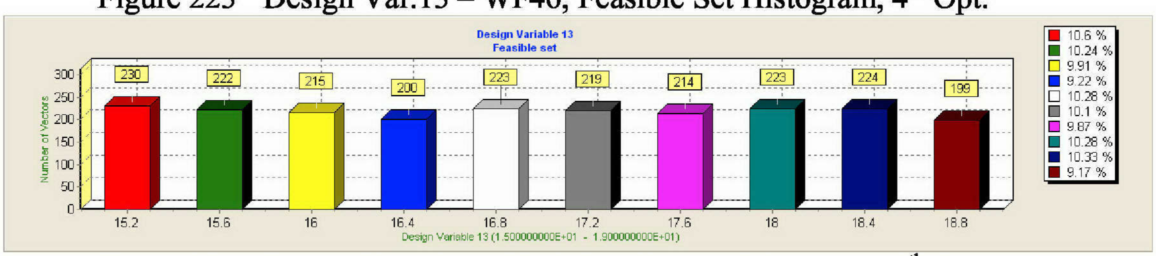

Figure 224 Design Var.13 – WF46, Feasible Set Histogram, 5th Opt.

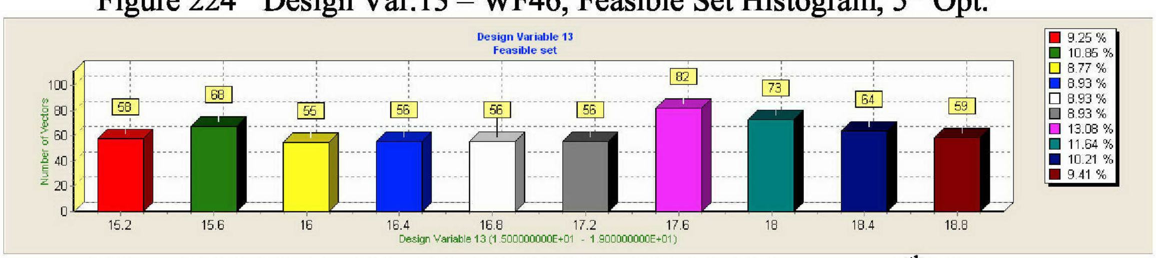

Figure 225 Design Var.13 – WF46, Feasible Set Histogram, 6th Opt.

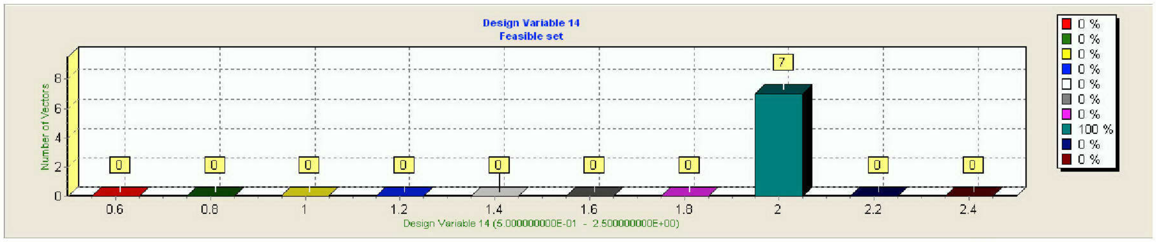

Figure 226 Design Var.14 – NP, DISCRETE, Feasible Set Histogram, 1st Opt.

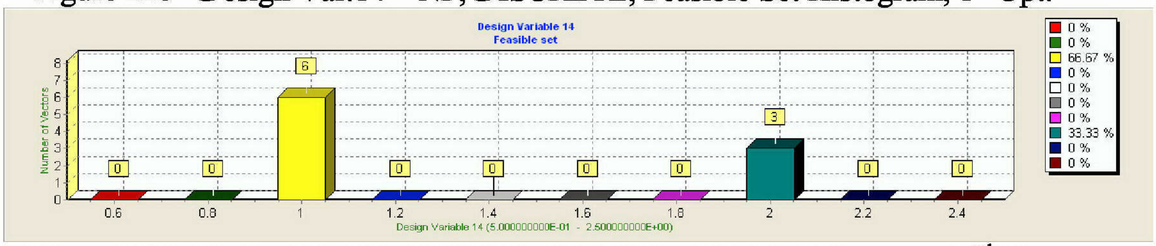

Figure 227 Design Var.14 – NP, DISCRETE, Feasible Set Histogram, 2nd Opt.

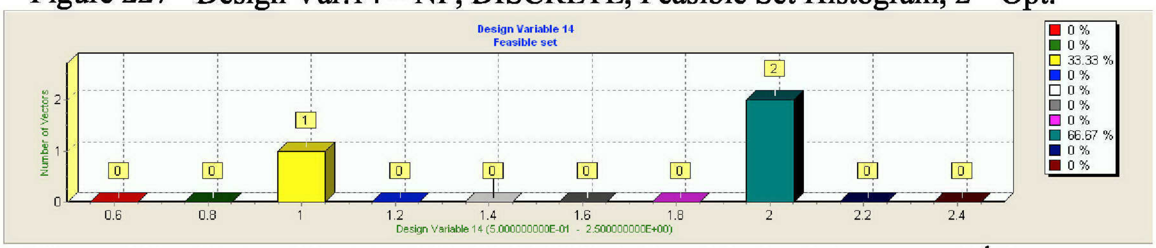

Figure 228 Design Var.14 – NP, DISCRETE, Feasible Set Histogram, 3rd Opt.

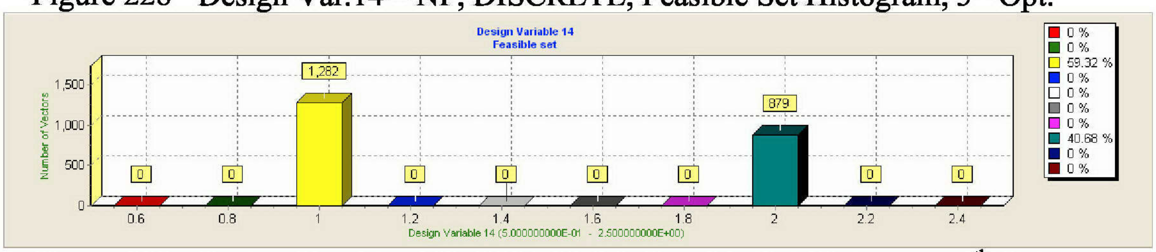

Figure 229 Design Var.14 – NP, DISCRETE, Feasible Set Histogram, 4th Opt.

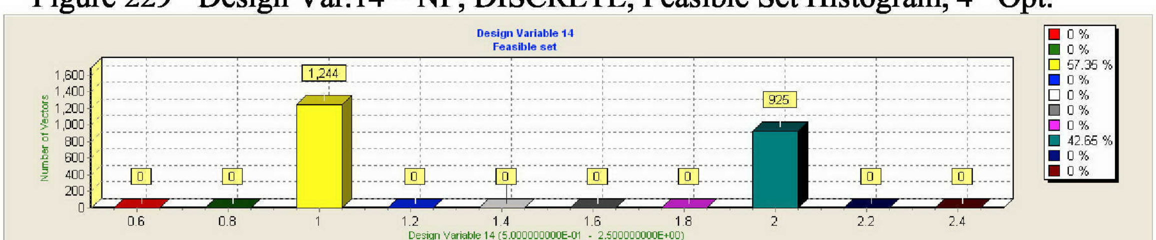

Figure 230 Design Var.14 – NP, DISCRETE, Feasible Set Histogram, 5th Opt.

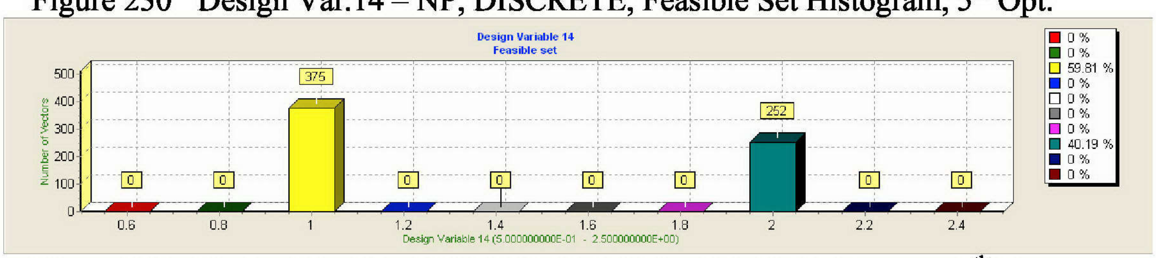

Figure 231 Design Var.14 – NP, DISCRETE, Feasible Set Histogram, 6th Opt.

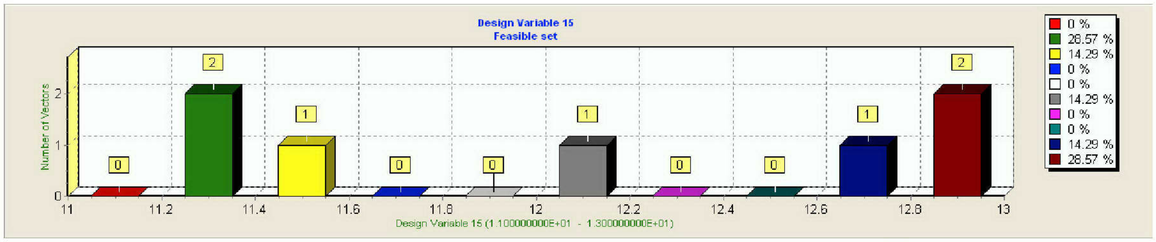

Figure 232 Design Var.15 – DP, Feasible Set Histogram, 1st Opt.

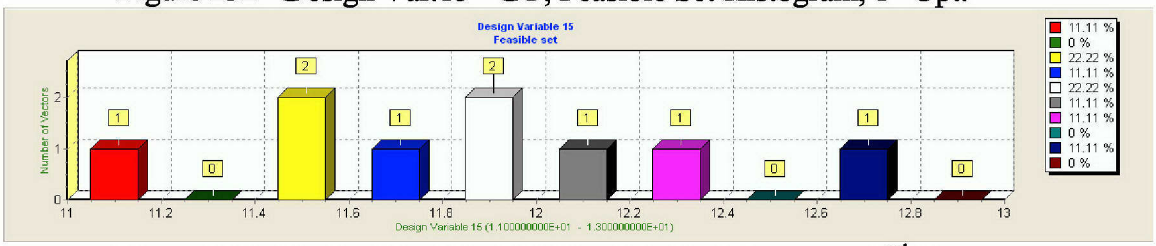

Figure 233 Design Var.15 – DP, Feasible Set Histogram, 2nd Opt.

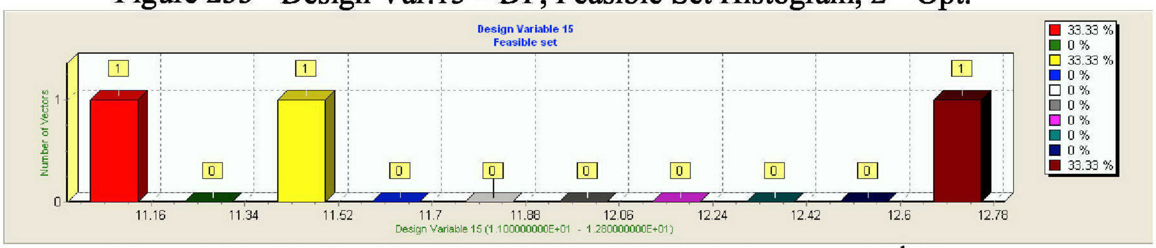

Figure 234 Design Var.15 – DP, Feasible Set Histogram, 3rd Opt.

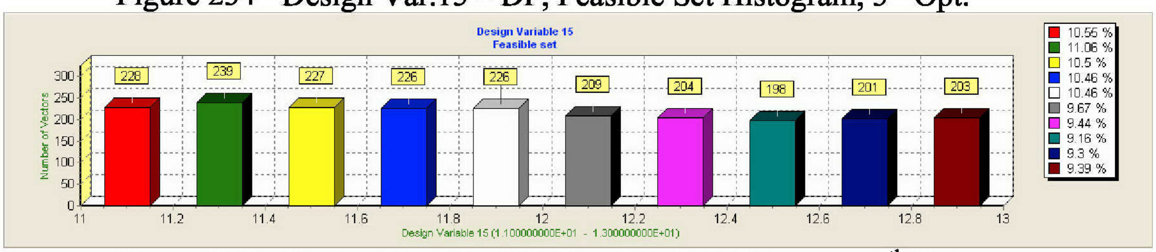

Figure 235 Design Var.15 – DP, Feasible Set Histogram, 4th Opt.

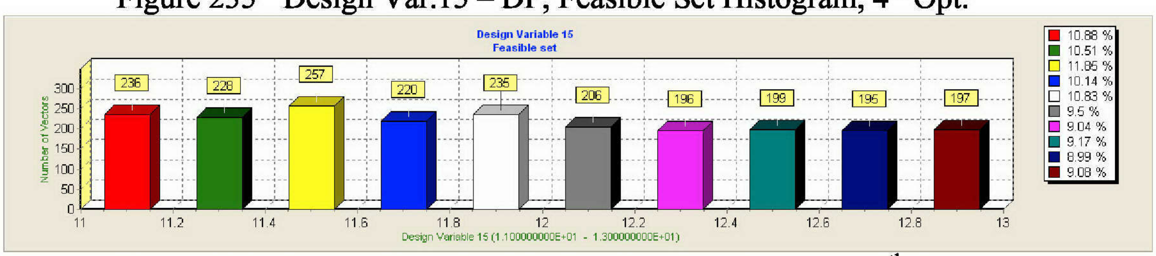

Figure 236 Design Var.15 – DP, Feasible Set Histogram, 5th Opt.

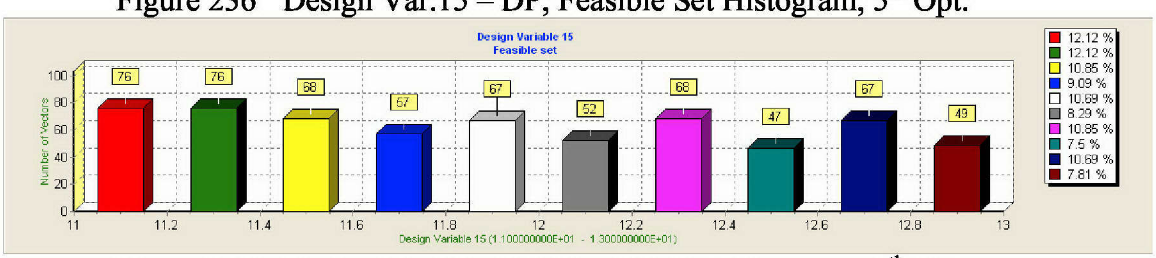

Figure 237 Design Var.15 – DP, Feasible Set Histogram, 6th Opt.

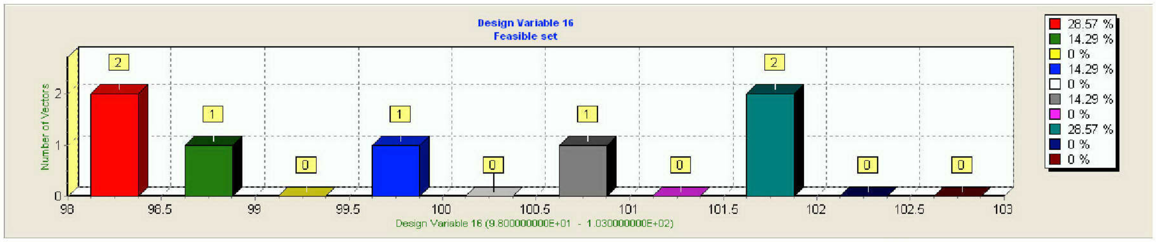

Figure 238 Design Var.16 – LS, Feasible Set Histogram, 1st Opt.

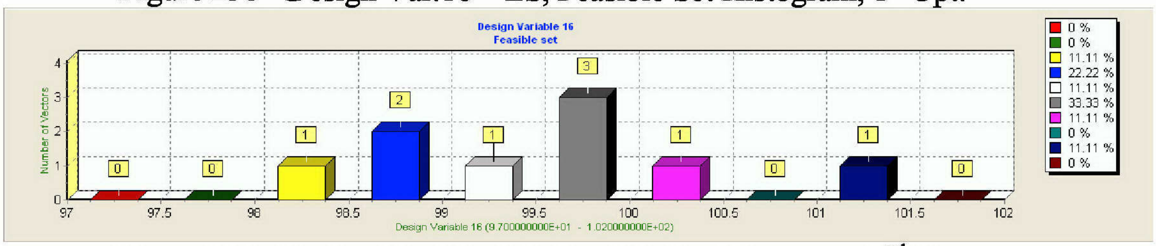

Figure 239 Design Var.16 – LS, Feasible Set Histogram, 2nd Opt.

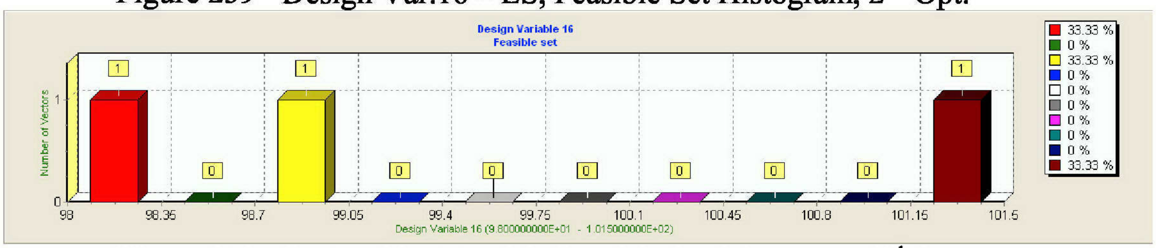

Figure 240 Design Var.16 – LS, Feasible Set Histogram, 3rd Opt.

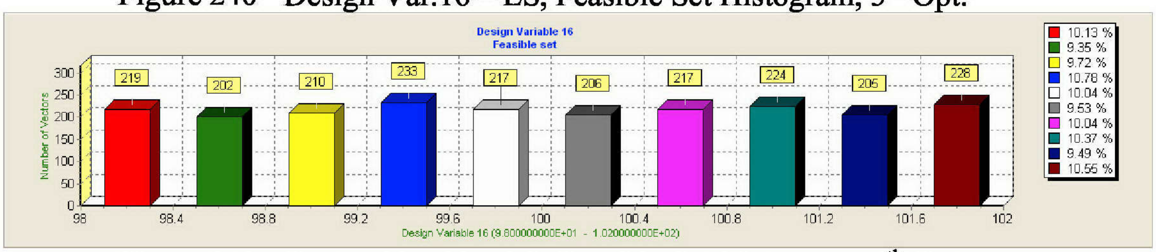

Figure 241 Design Var.16 – LS, Feasible Set Histogram, 4th Opt.

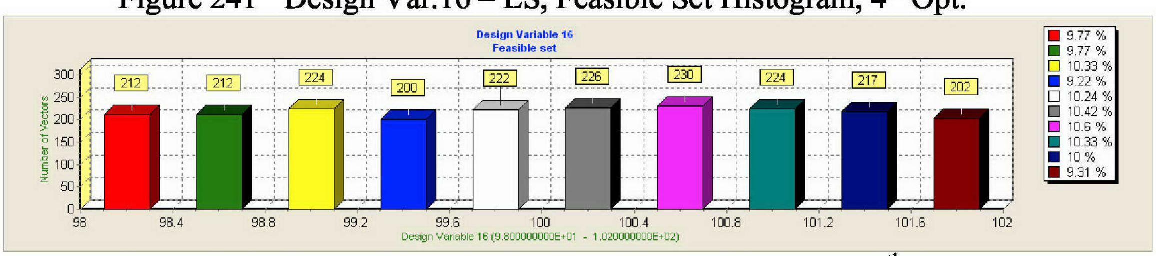

Figure 242 Design Var.16 – LS, Feasible Set Histogram, 5th Opt.

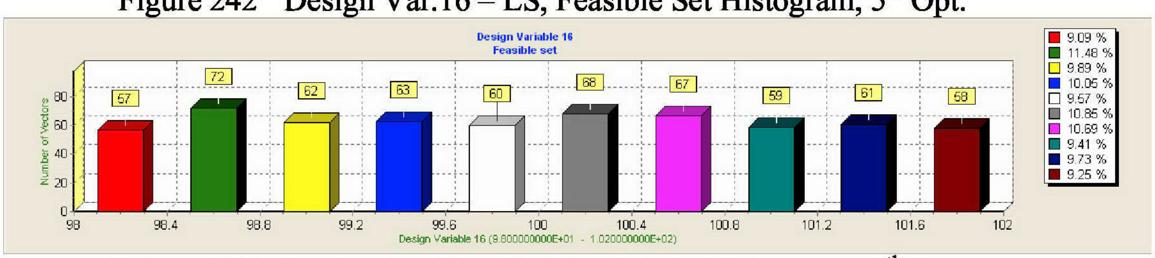

Figure 243 Design Var.16 – LS, Feasible Set Histogram, 6th Opt.

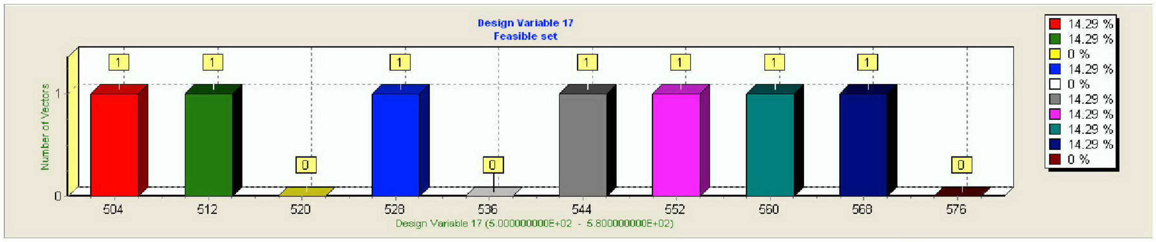

Figure 244 Design Var.17 – ADB, Feasible Set Histogram, 1st Opt.

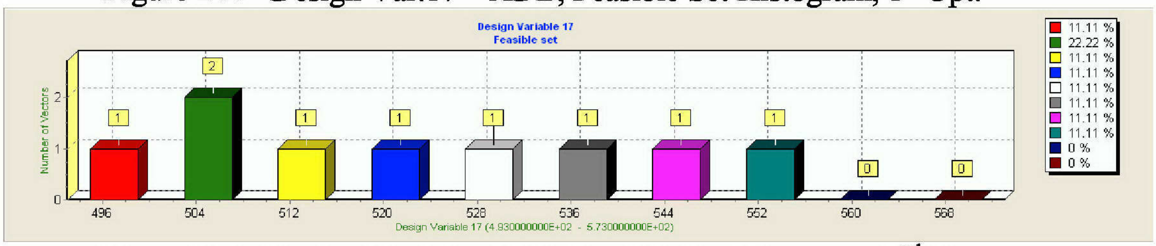

Figure 245 Design Var.17 – ADB, Feasible Set Histogram, 2nd Opt.

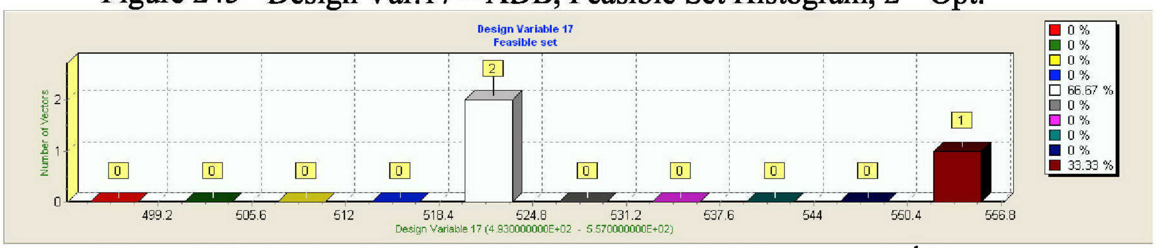

Figure 246 Design Var.17 – ADB, Feasible Set Histogram, 3rd Opt.

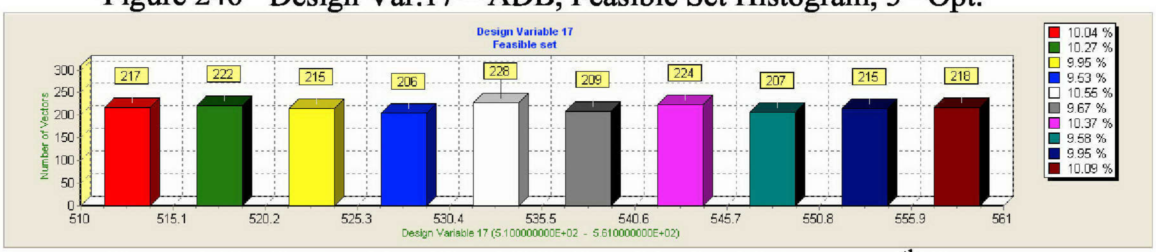

Figure 247 Design Var.17 – ADB, Feasible Set Histogram, 4th Opt.

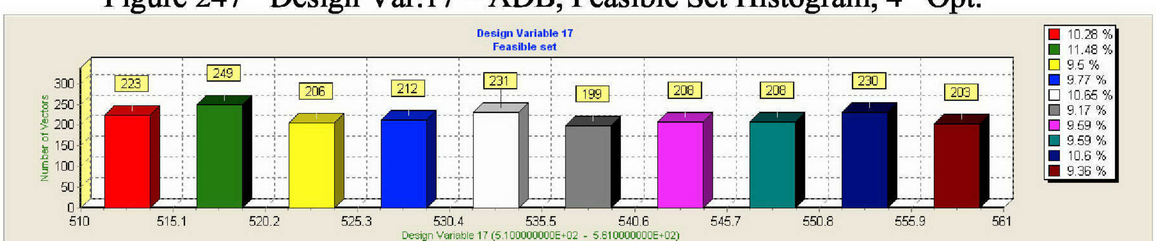

Figure 248 Design Var.17 – ADB, Feasible Set Histogram, 5th Opt.

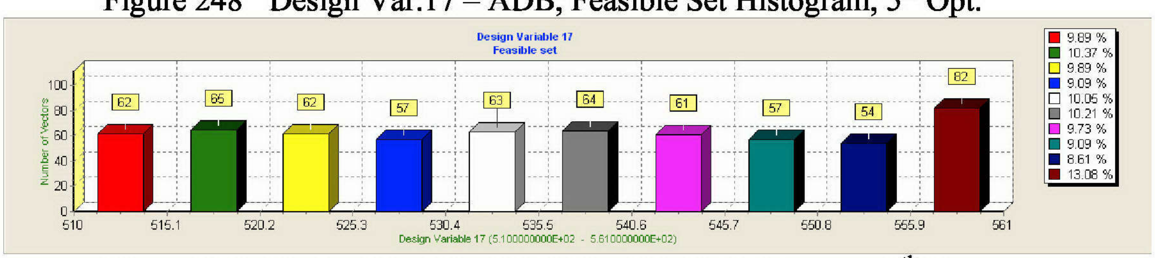

Figure 249 Design Var.17 – ADB, Feasible Set Histogram, 6th Opt.

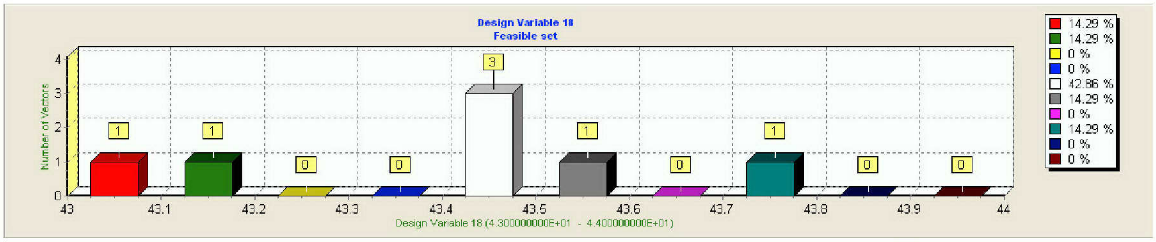

Figure 250 Design Var.18 – WIC, Feasible Set Histogram, 1st Opt.

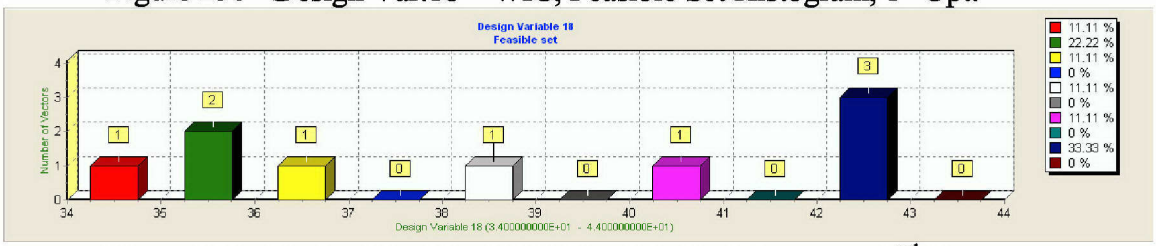

Figure 251 Design Var.18 – WIC, Feasible Set Histogram, 2nd Opt.

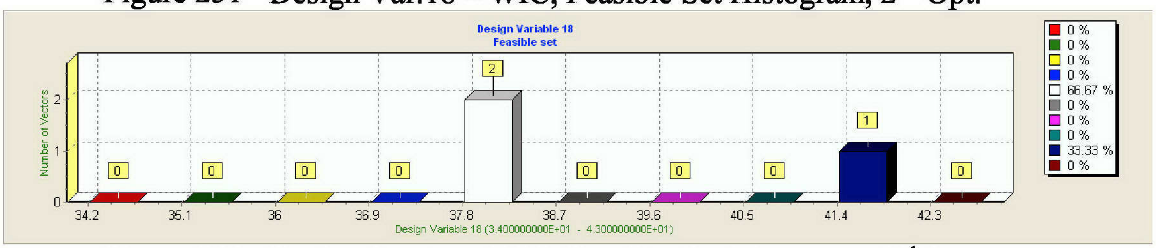

Figure 252 Design Var.18 – WIC, Feasible Set Histogram, 3rd Opt.

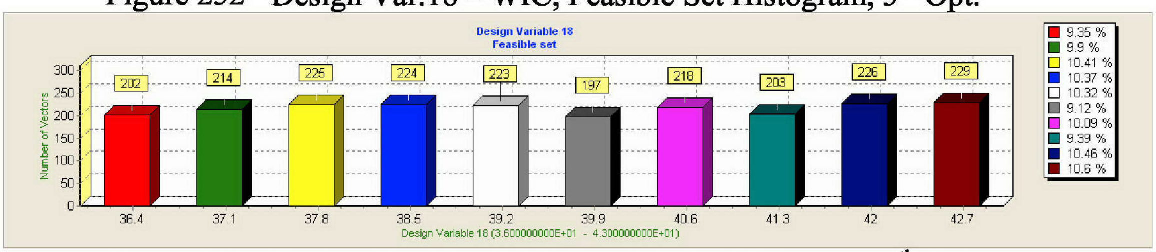

Figure 253 Design Var.18 – WIC, Feasible Set Histogram, 4th Opt.

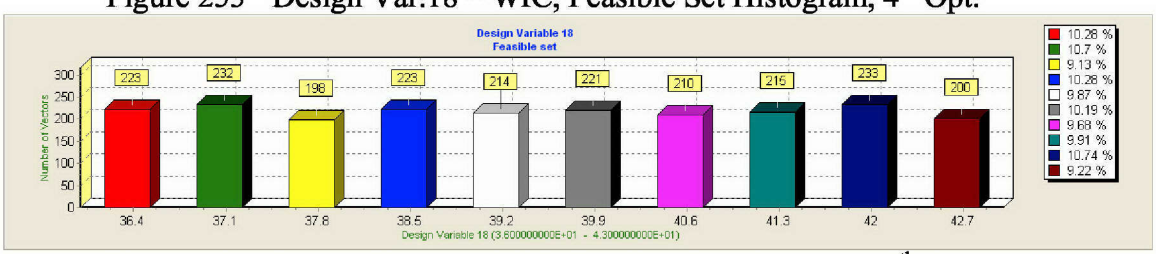

Figure 254 Design Var.18 – WIC, Feasible Set Histogram, 5th Opt.

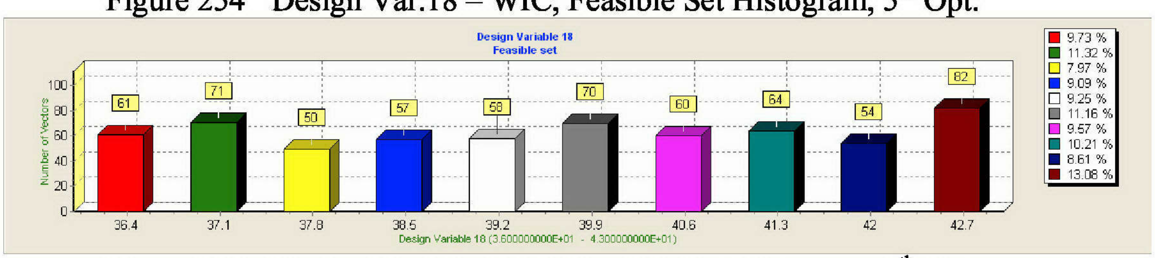

Figure 255 Design Var.18 – WIC, Feasible Set Histogram, 6th Opt.

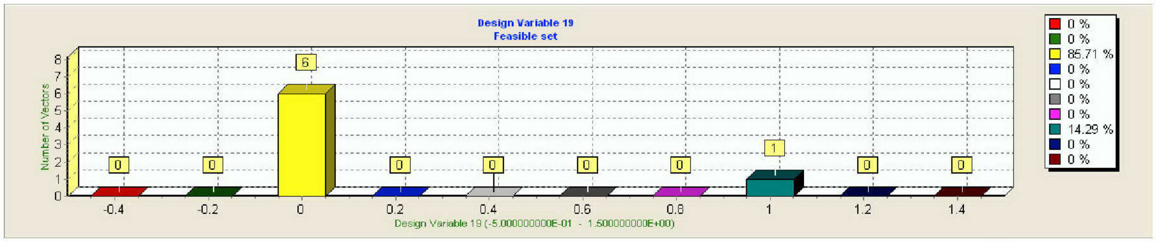

Figure 256 Design Var.19 – Nfins, DISCRETE, Feasible Set Histogram, 1st Opt.

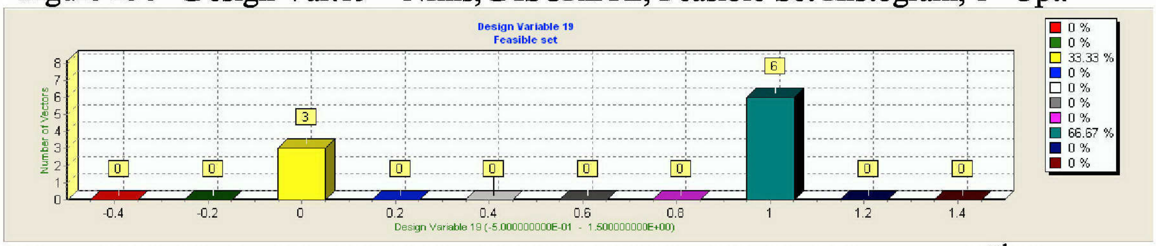

Figure 257 Design Var.19 – Nfins, DISCRETE, Feasible Set Histogram, 2nd Opt.

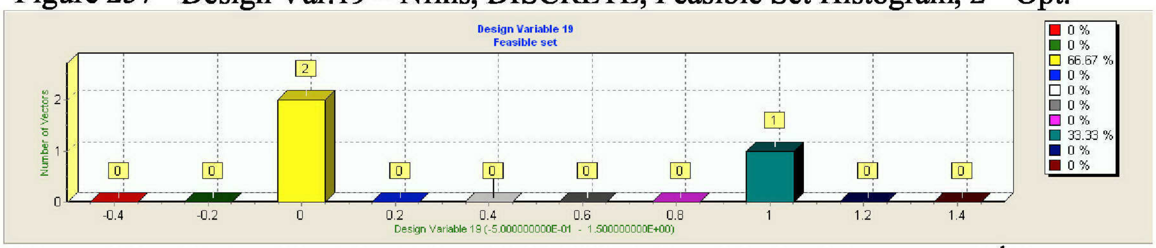

Figure 258 Design Var.19 – Nfins, DISCRETE, Feasible Set Histogram, 3rd Opt.

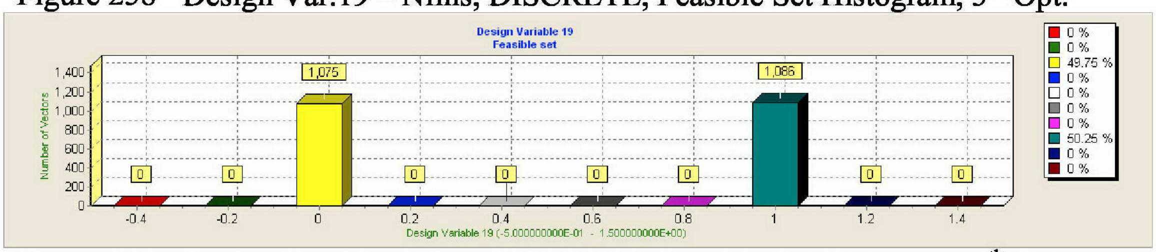

Figure 259 Design Var.19 – Nfins, DISCRETE, Feasible Set Histogram, 4th Opt.

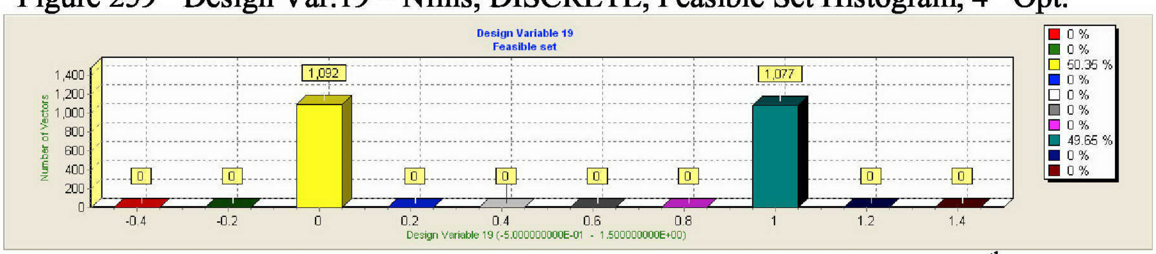

Figure 260 Design Var.19 – Nfins, DISCRETE, Feasible Set Histogram, 5th Opt.

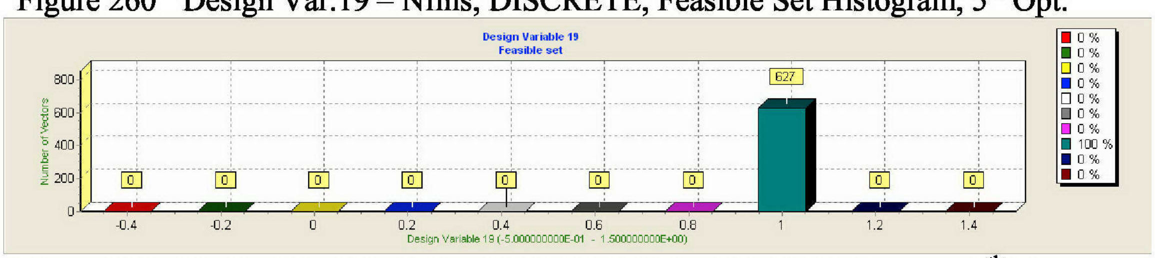

Figure 261 Design Var.19 – Nfins, DISCRETE, Feasible Set Histogram, 6th Opt.

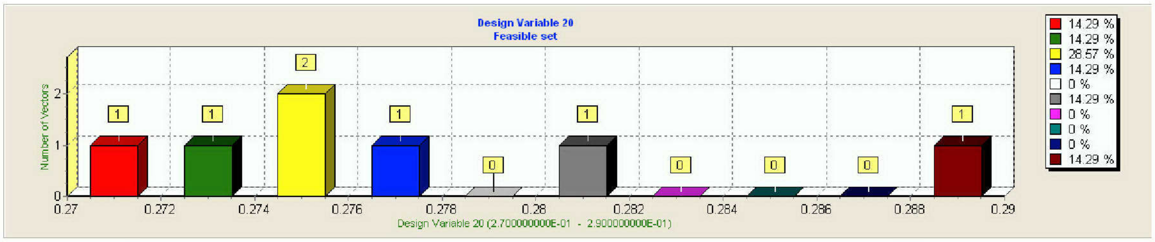

Figure 262 Design Var.20 – CSD, Feasible Set Histogram, 1st Opt.

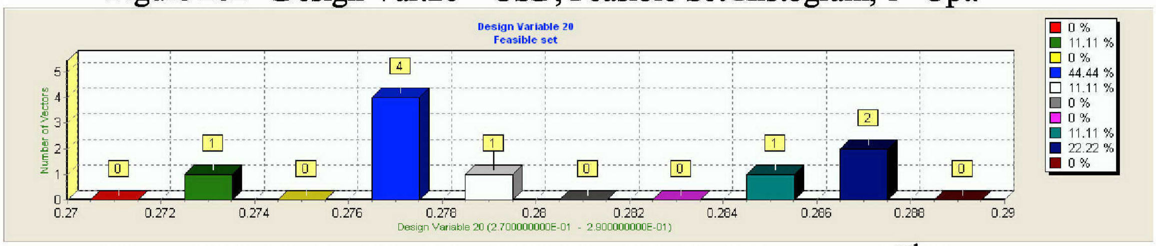

Figure 263 Design Var.20 – CSD, Feasible Set Histogram, 2nd Opt.

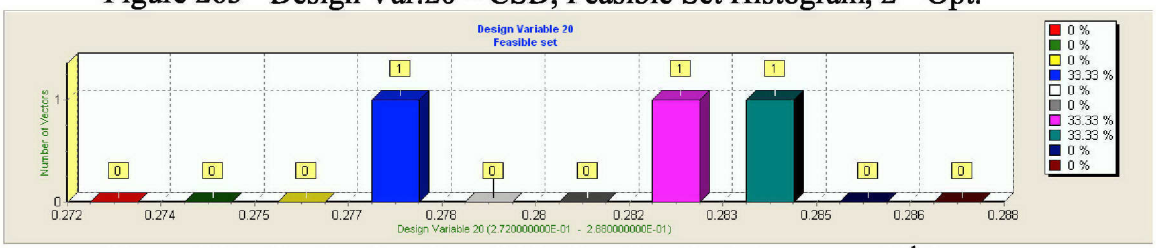

Figure 264 Design Var.20 – CSD, Feasible Set Histogram, 3rd Opt.

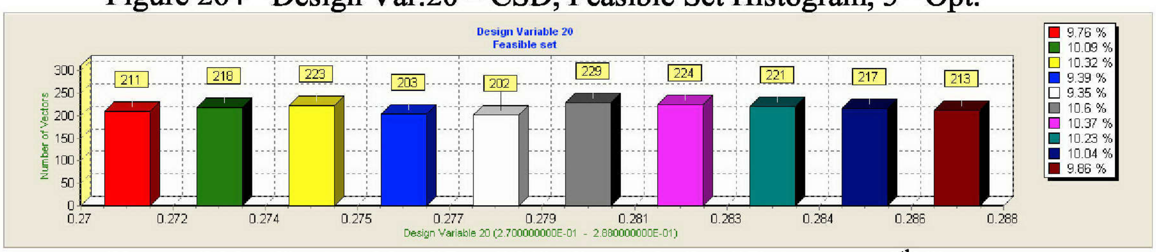

Figure 265 Design Var.20 – CSD, Feasible Set Histogram, 4th Opt.

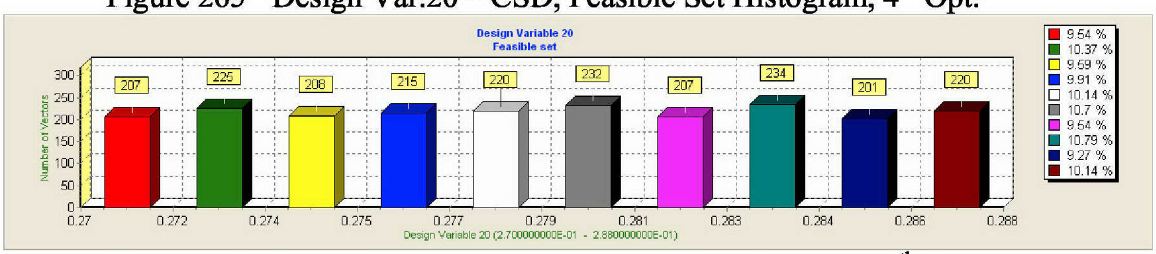

Figure 266 Design Var.20 – CSD, Feasible Set Histogram, 5th Opt.

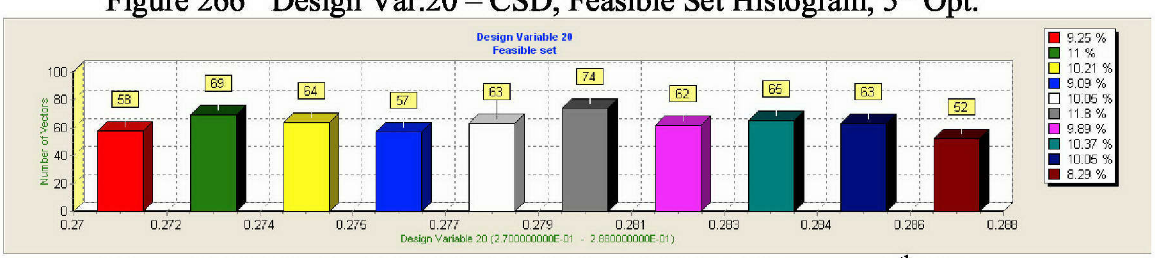

Figure 267 Design Var.20 – CSD, Feasible Set Histogram, 6th Opt.

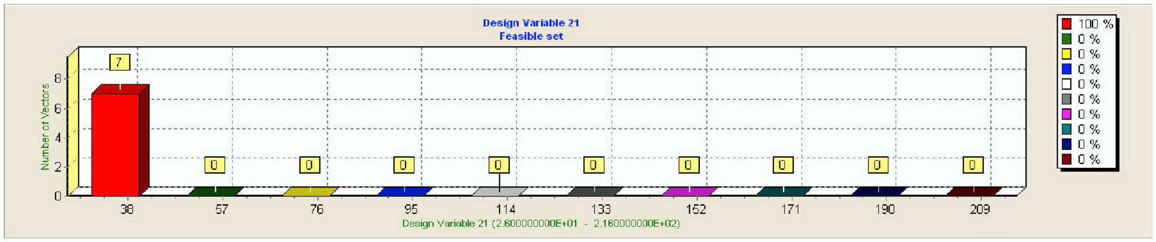

Figure 268 Design Var.21 – ASD, DISCRETE, Feasible Set Histogram, 1st Opt.

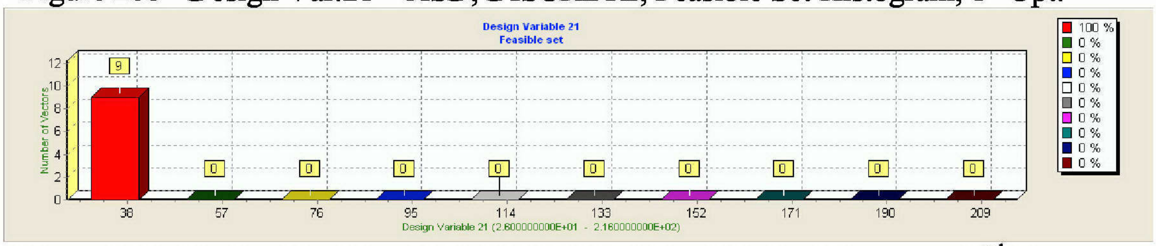

Figure 269 Design Var.21 – ASD, DISCRETE, Feasible Set Histogram, 2nd Opt.

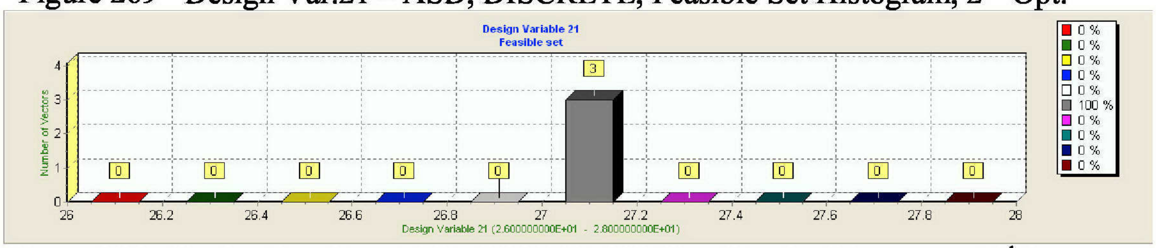

Figure 270 Design Var.21 – ASD, **CONSTANT**, Feasible Set Histogram, 3rd Opt.

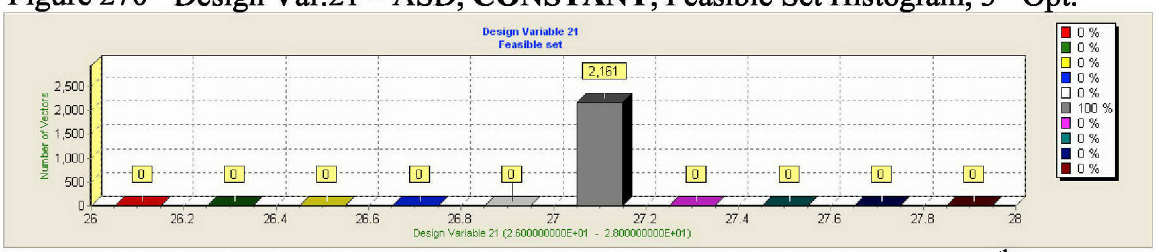

Figure 271 Design Var.21 – ASD, **CONSTANT**, Feasible Set Histogram, 4th Opt.

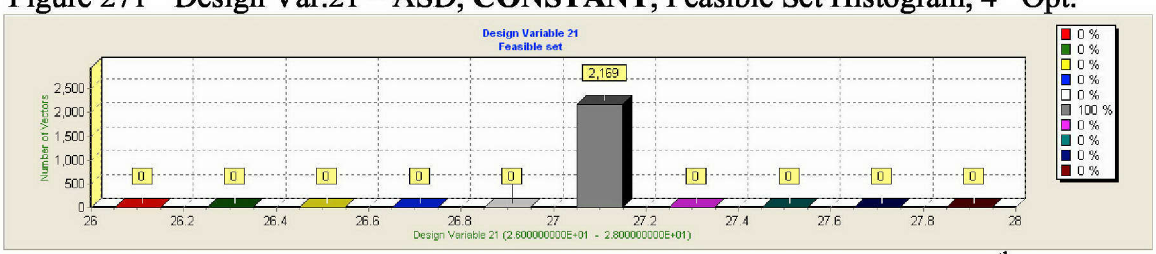

Figure 272 Design Var.21 – ASD, **CONSTANT**, Feasible Set Histogram, 5th Opt.

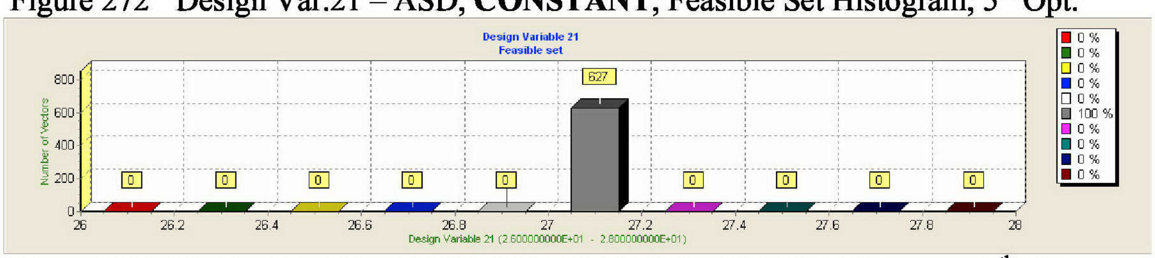

Figure 273 Design Var.21 – ASD, **CONSTANT**, Feasible Set Histogram, 6th Opt.

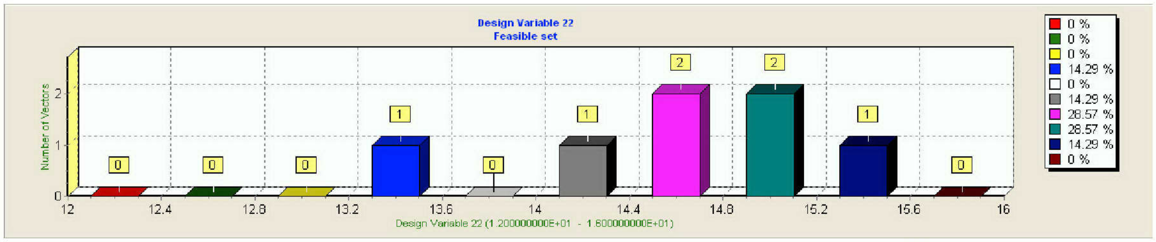

Figure 274 Design Var.22 – W498, Feasible Set Histogram, 1st Opt.

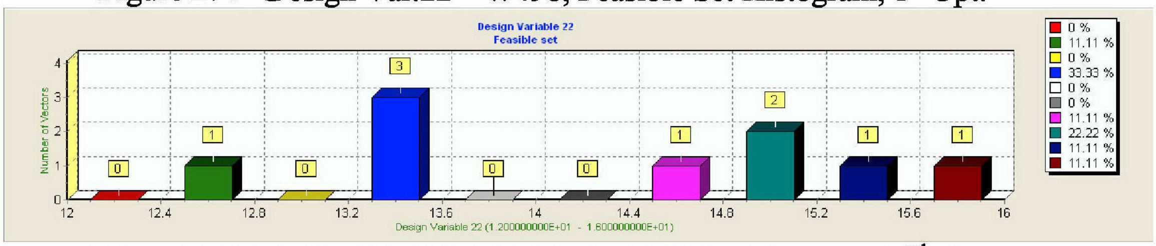

Figure 275 Design Var.22 – W498, Feasible Set Histogram, 2nd Opt.

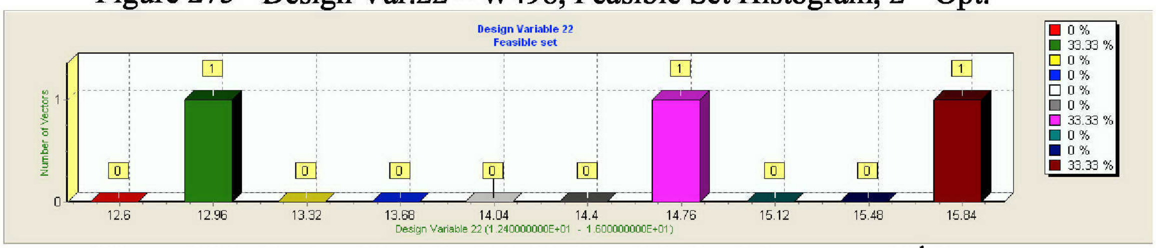

Figure 276 Design Var.22 – W498, Feasible Set Histogram, 3rd Opt.

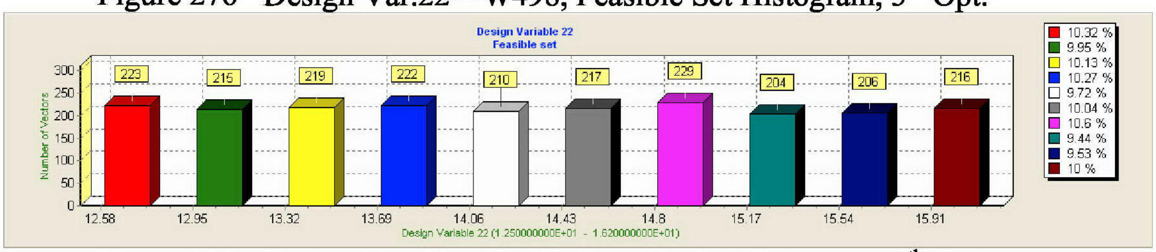

Figure 277 Design Var.22 – W498, Feasible Set Histogram, 4th Opt.

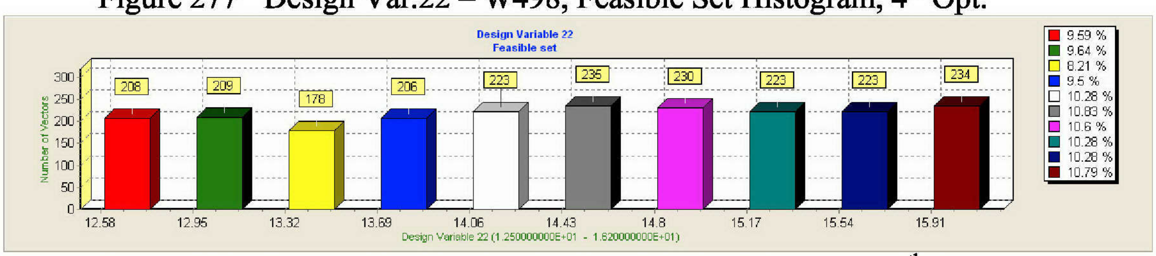

Figure 278 Design Var.22 – W498, Feasible Set Histogram, 5th Opt.

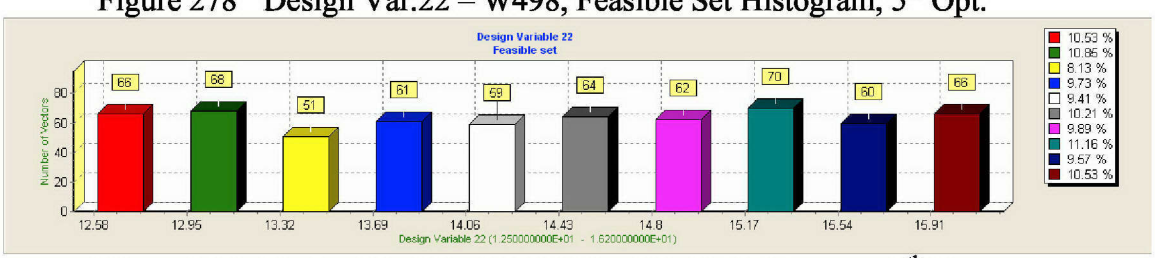

Figure 279 Design Var.22 – W498, Feasible Set Histogram, 6th Opt.

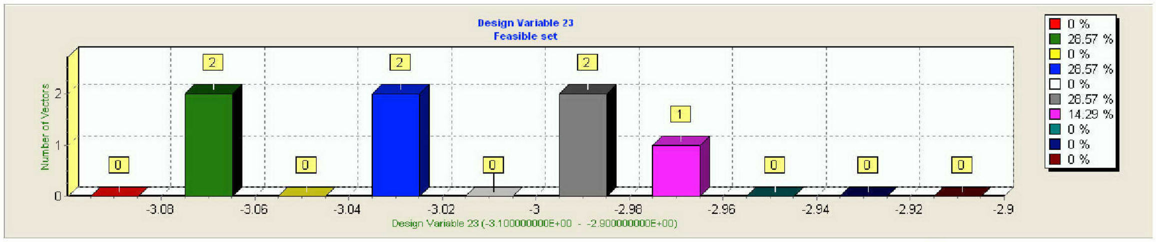

Figure 280 Design Var.23 – VCG498, Feasible Set Histogram, 1st Opt.

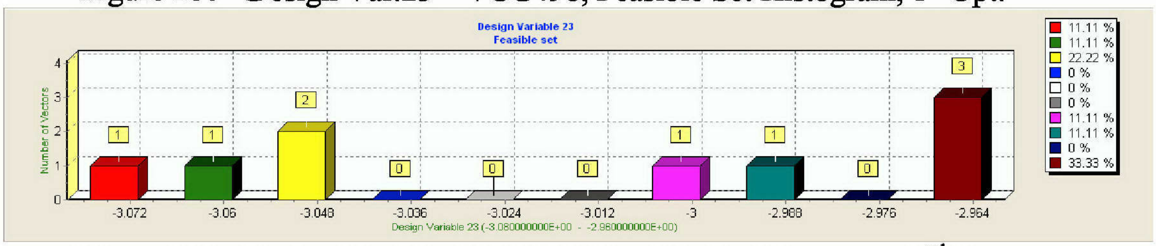

Figure 281 Design Var.23 – VCG498, Feasible Set Histogram, 2nd Opt.

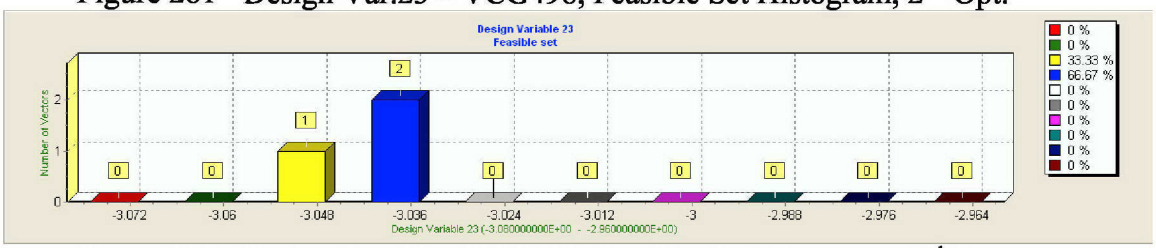

Figure 282 Design Var.23 – VCG498, Feasible Set Histogram, 3rd Opt.

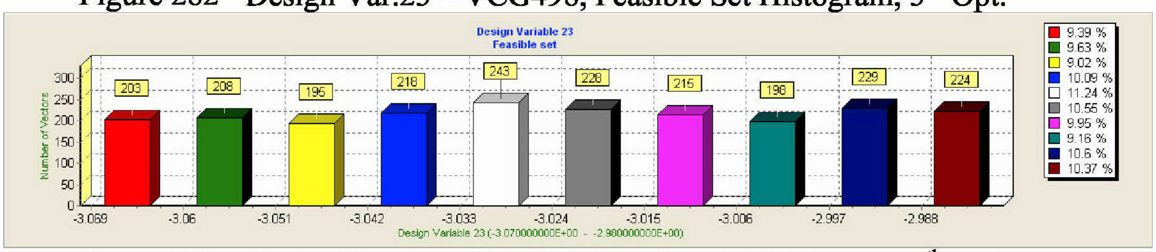

Figure 283 Design Var.23 – VCG498, Feasible Set Histogram, 4th Opt.

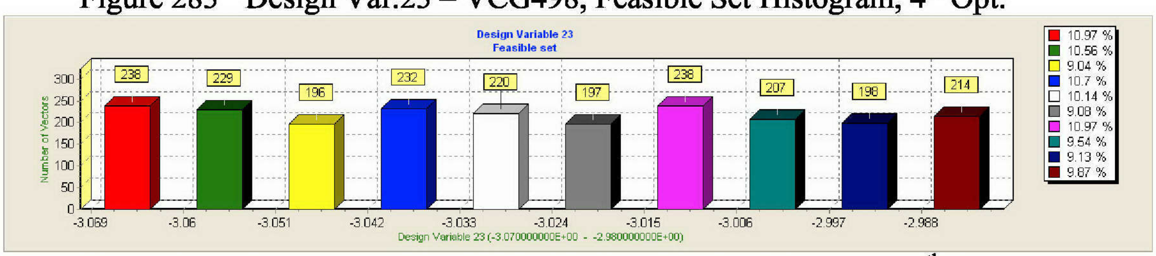

Figure 284 Design Var.23 – VCG498, Feasible Set Histogram, 5th Opt.

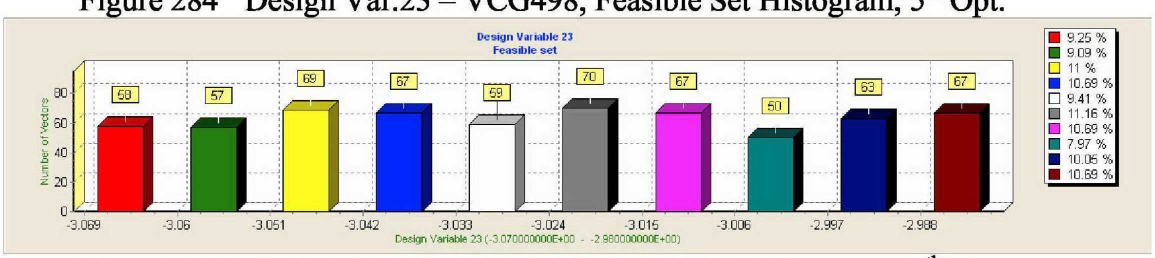

Figure 285 Design Var.23 – VCG498, Feasible Set Histogram, 6th Opt.

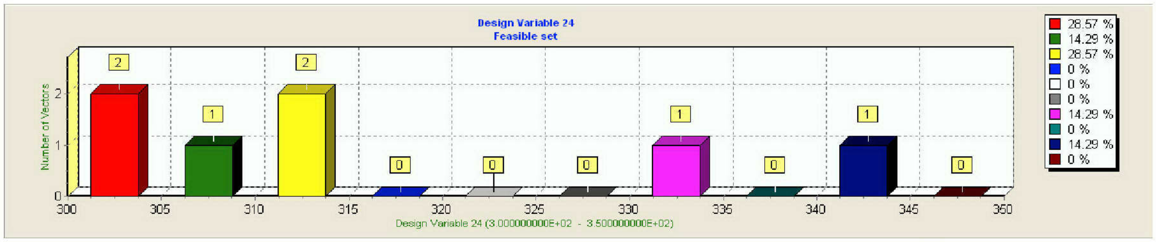

Figure 286 Design Var.24 – ACOXO, Feasible Set Histogram, 1st Opt.

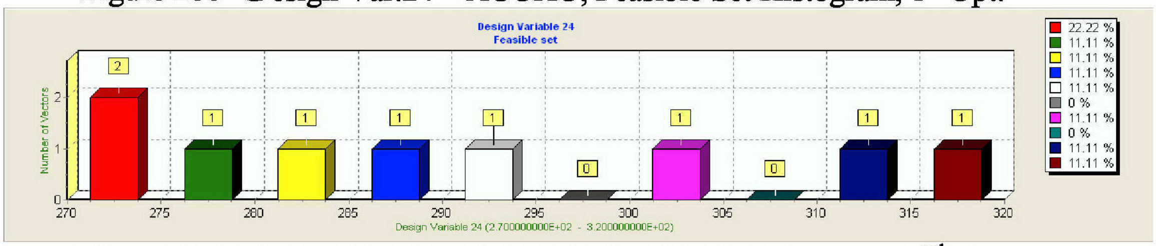

Figure 287 Design Var.24 – ACOXO, Feasible Set Histogram, 2nd Opt.

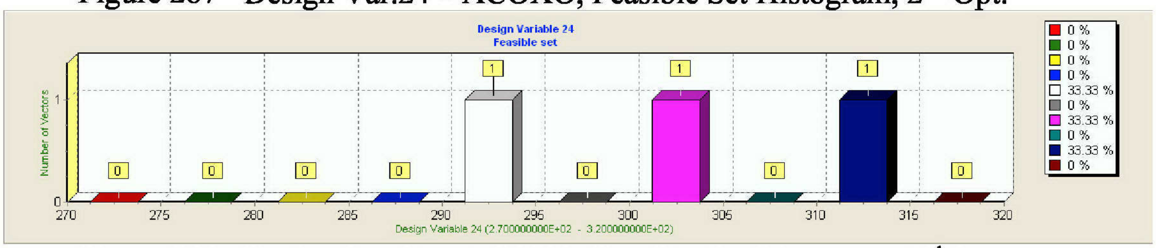

Figure 288 Design Var.24 – ACOXO, Feasible Set Histogram, 3rd Opt.

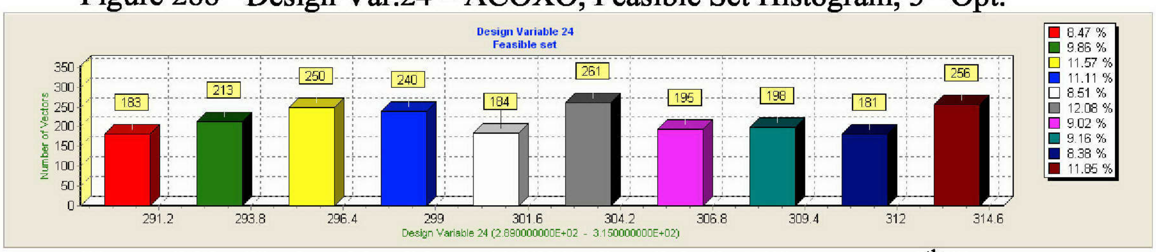

Figure 289 Design Var.24 – ACOXO, Feasible Set Histogram, 4th Opt.

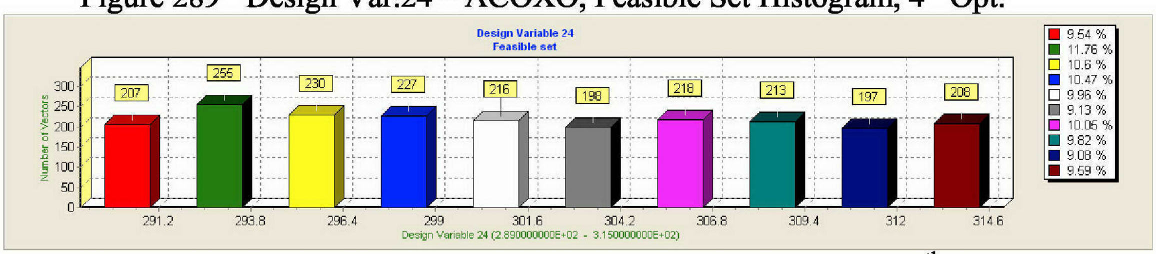

Figure 290 Design Var.24 – ACOXO, Feasible Set Histogram, 5th Opt.

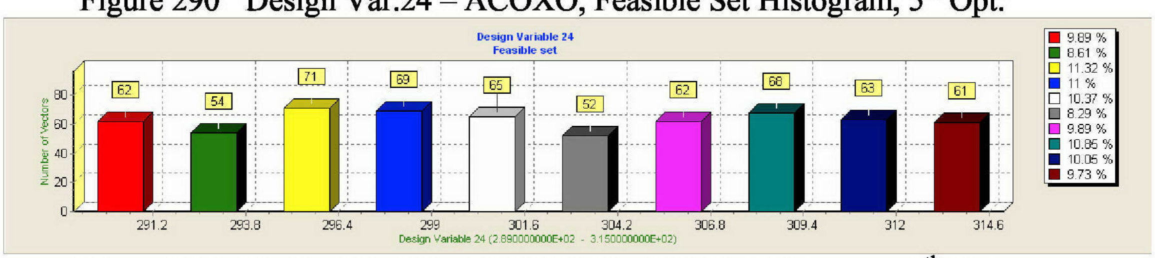

Figure 291 Design Var.24 – ACOXO, Feasible Set Histogram, 6th Opt.

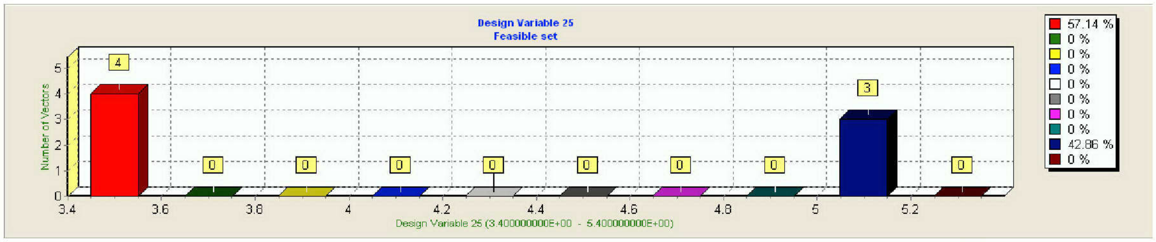

Figure 292 Design Var.25 – vf, DISCRETE, Feasible Set Histogram, 1st Opt.

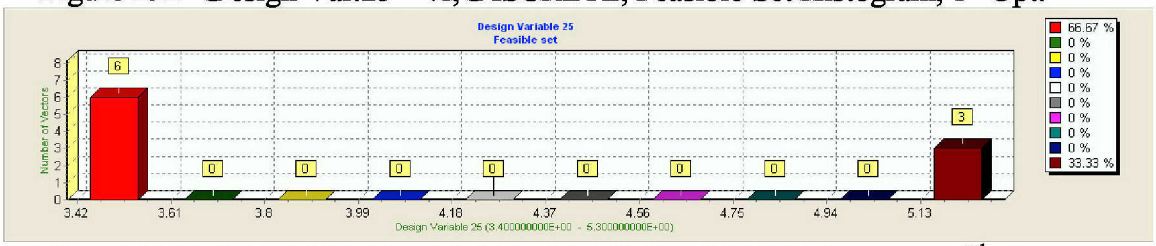

Figure 293 Design Var.25 – vf, DISCRETE, Feasible Set Histogram, 2nd Opt.

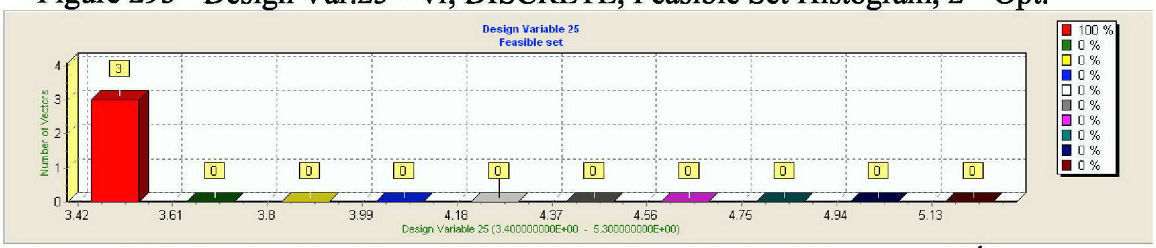

Figure 294 Design Var.25 – vf, DISCRETE, Feasible Set Histogram, 3rd Opt.

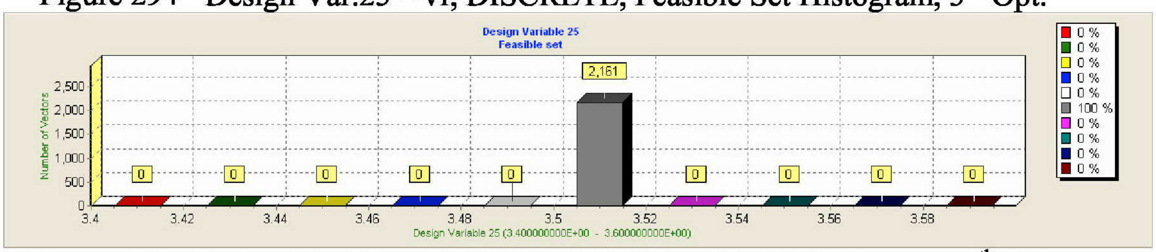

Figure 295 Design Var.25 – vf, **CONSTANT**, Feasible Set Histogram, 4th Opt.

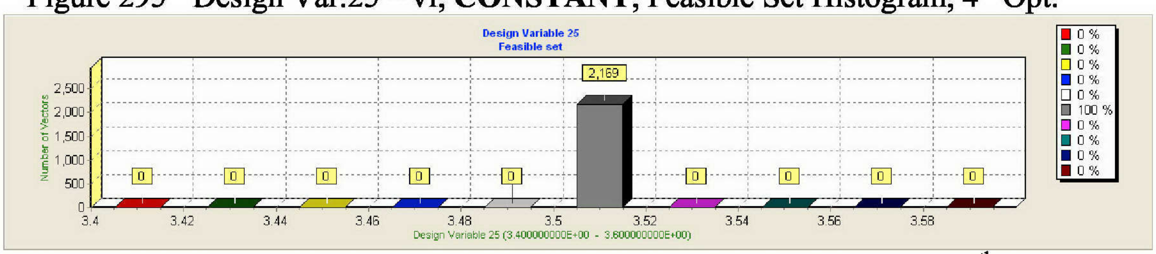

Figure 296 Design Var.25 – vf, **CONSTANT**, Feasible Set Histogram, 5th Opt.

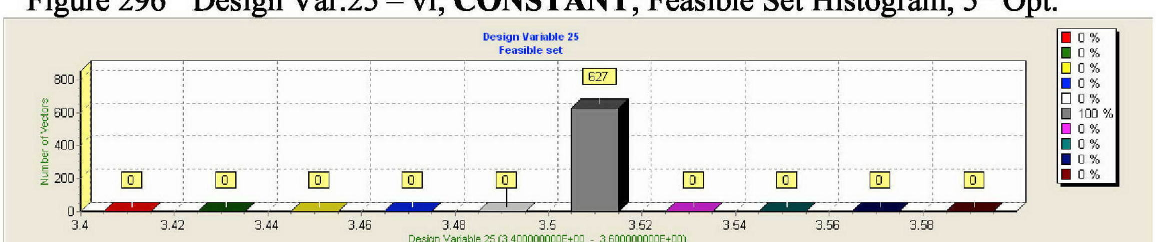

Figure 297 Design Var.25 – vf, **CONSTANT**, Feasible Set Histogram, 6th Opt.

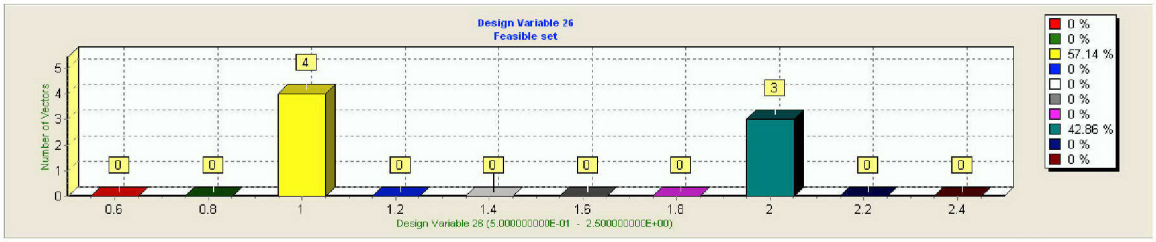

Figure 298 Design Var.26 – CDHMAT, DISCRETE, Feasible Set Histogram, 1st Opt.

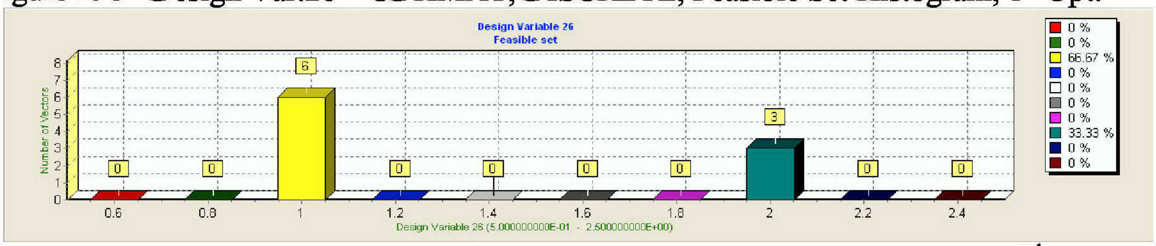

Figure 299 Design Var.26 – CDHMAT, DISCRETE, Feasible Set Histogram, 2nd Opt.

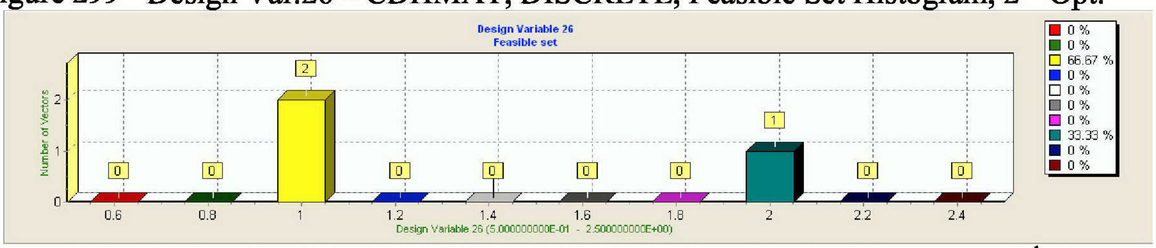

Figure 300 Design Var.26 – CDHMAT, DISCRETE, Feasible Set Histogram, 3rd Opt.

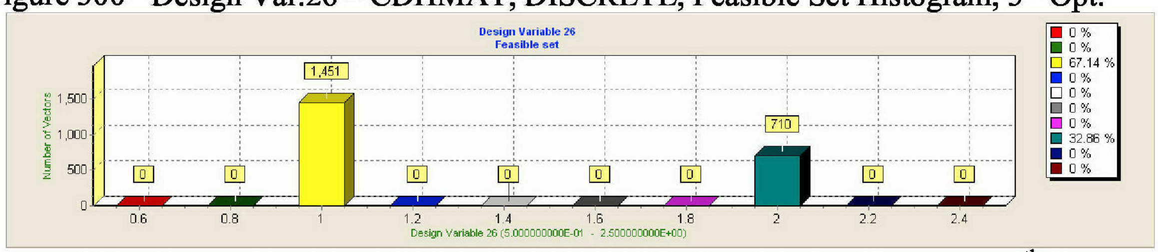

Figure 301 Design Var.26 – CDHMAT, DISCRETE, Feasible Set Histogram, 4th Opt.

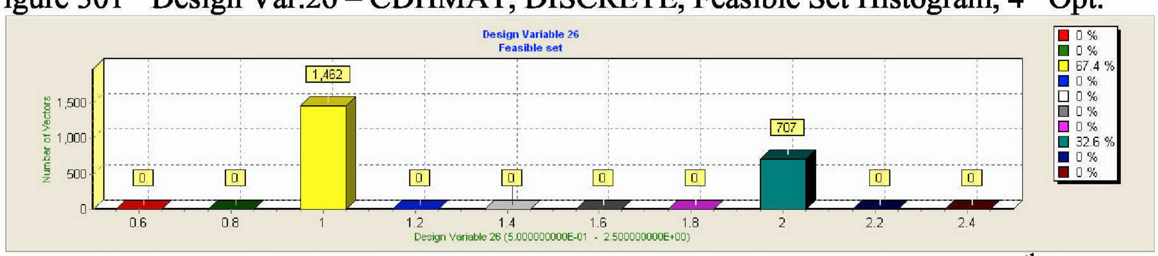

Figure 302 Design Var.26 – CDHMAT, DISCRETE, Feasible Set Histogram, 5th Opt.

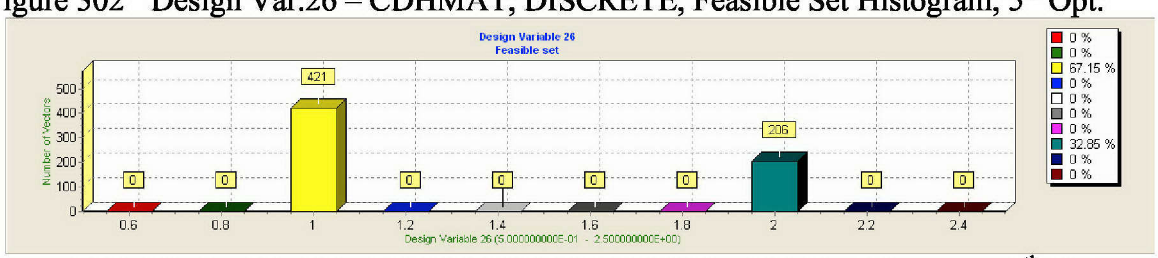

Figure 303 Design Var.26 – CDHMAT, DISCRETE, Feasible Set Histogram, 6th Opt.

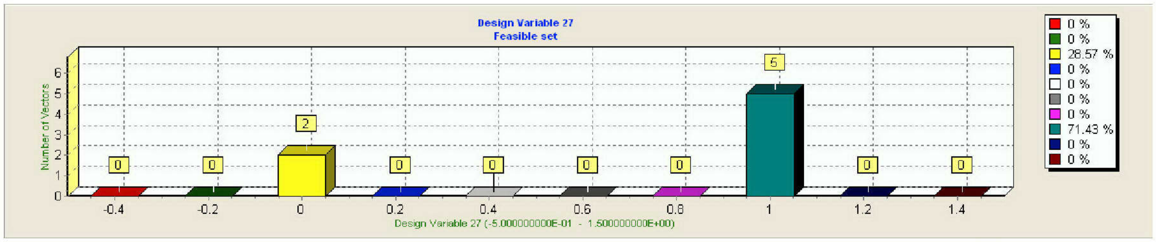

Figure 304 Design Var.27 – CPS, DISCRETE, Feasible Set Histogram, 1st Opt.

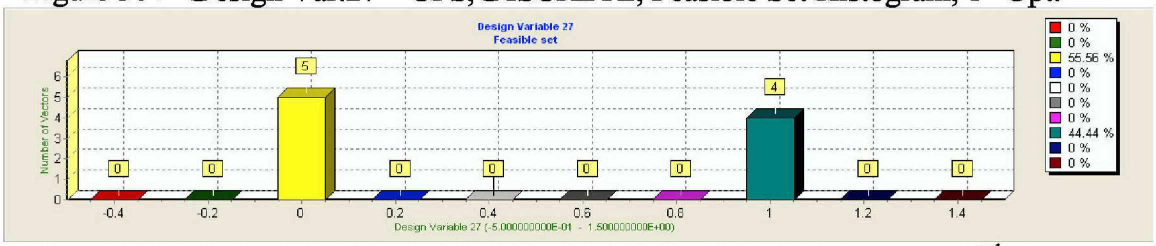

Figure 305 Design Var.27 – CPS, DISCRETE, Feasible Set Histogram, 2nd Opt.

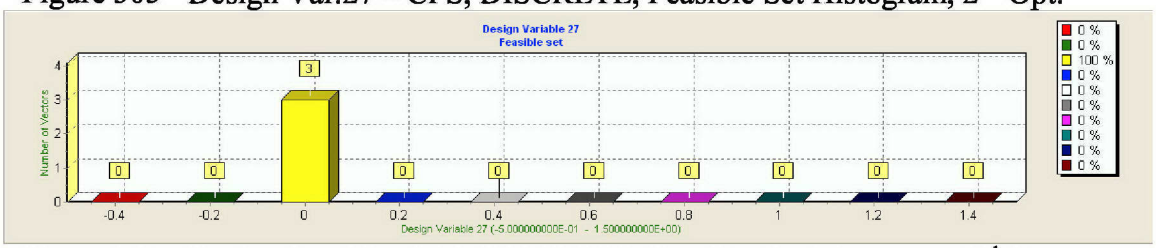

Figure 306 Design Var.27 – CPS, DISCRETE, Feasible Set Histogram, 3rd Opt.

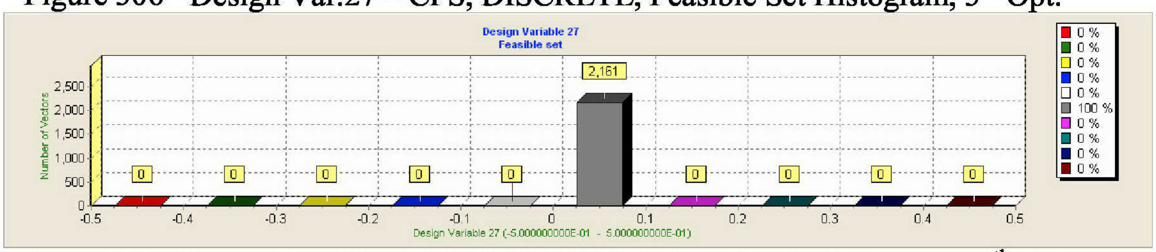

Figure 307 Design Var.27 – CPS, **CONSTANT**, Feasible Set Histogram, 4th Opt.

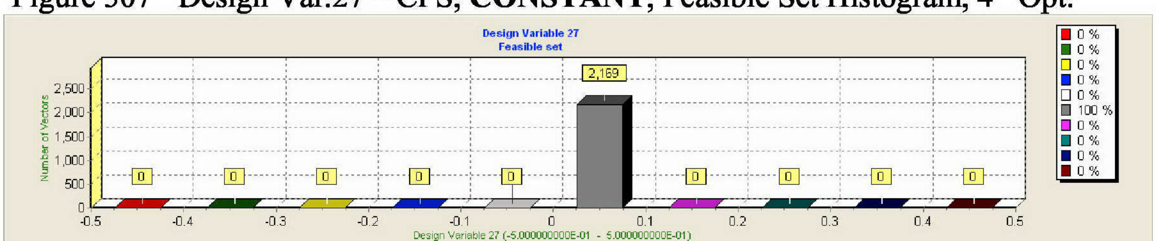

Figure 308 Design Var.27 – CPS, **CONSTANT**, Feasible Set Histogram, 5th Opt.

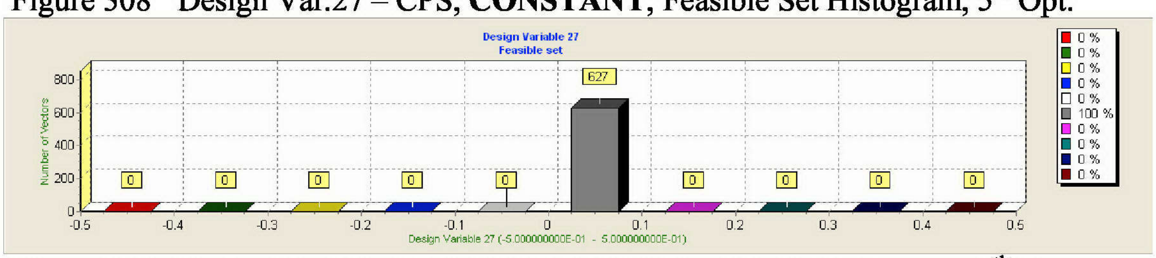

Figure 309 Design Var.27 – CPS, **CONSTANT**, Feasible Set Histogram, 6th Opt.

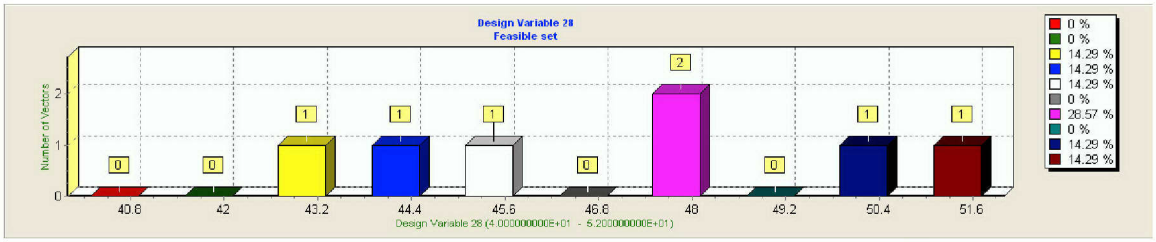

Figure 310 Design Var.28 – kWM, Feasible Set Histogram, 1st Opt.

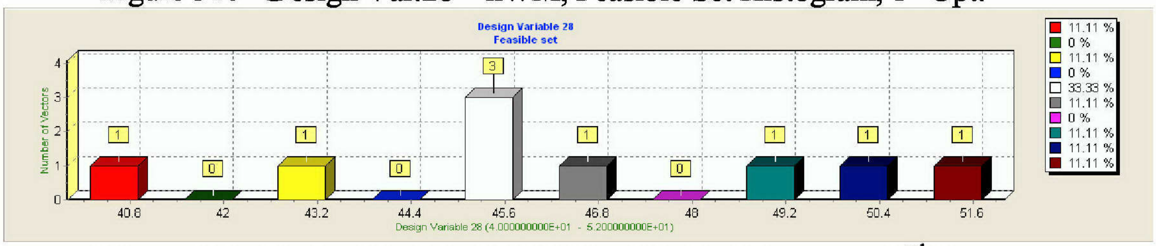

Figure 311 Design Var.28 – kWM, Feasible Set Histogram, 2nd Opt.

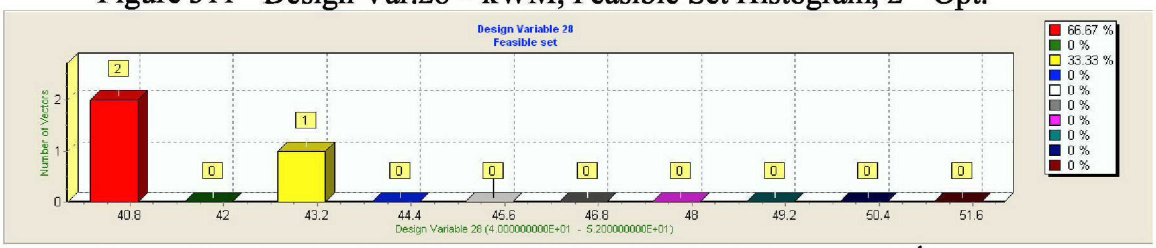

Figure 312 Design Var.28 – kWM, Feasible Set Histogram, 3rd Opt.

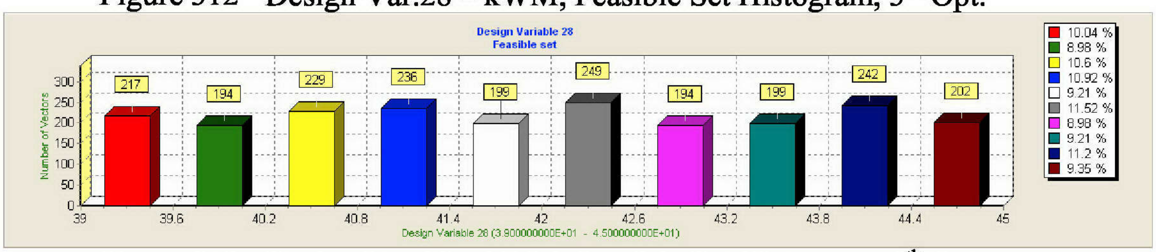

Figure 313 Design Var.28 – kWM, Feasible Set Histogram, 4th Opt.

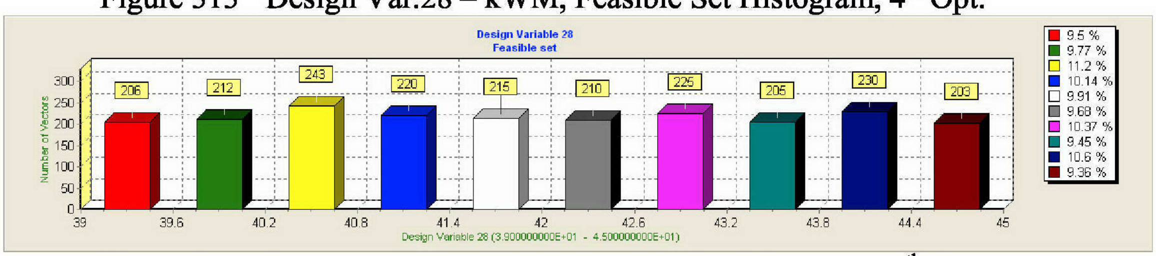

Figure 314 Design Var.28 – kWM, Feasible Set Histogram, 5th Opt.

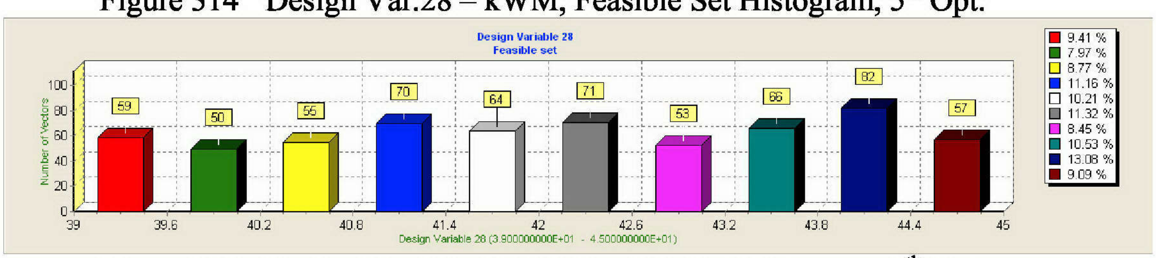

Figure 315 Design Var.28 – kWM, Feasible Set Histogram, 6th Opt.

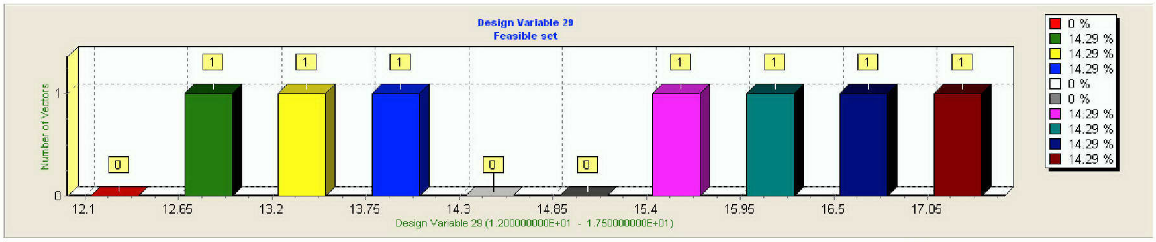

Figure 316 Design Var.29 – W593, Feasible Set Histogram, 1st Opt.

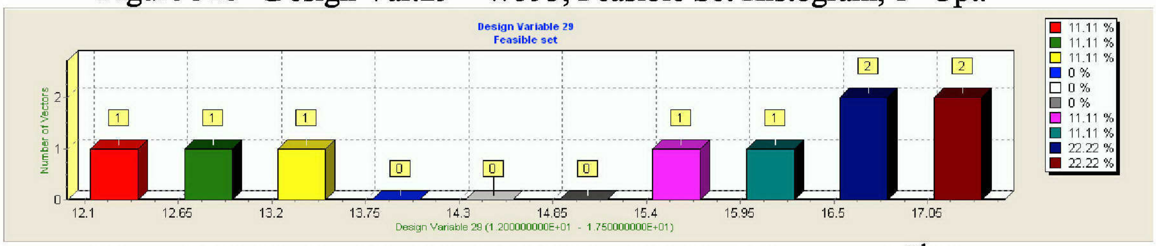

Figure 317 Design Var.29 – W593, Feasible Set Histogram, 2nd Opt.

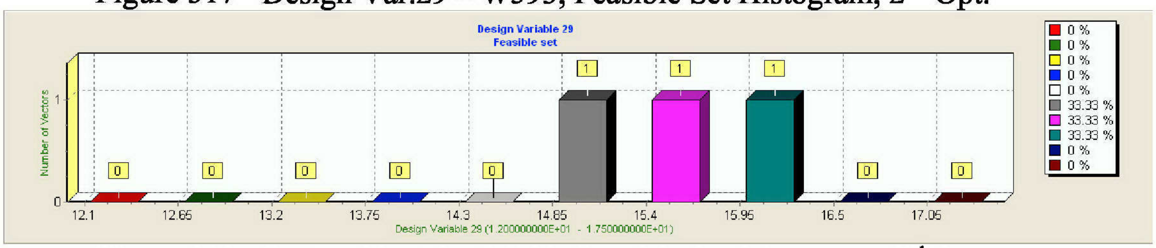

Figure 318 Design Var.29 – W593, Feasible Set Histogram, 3rd Opt.

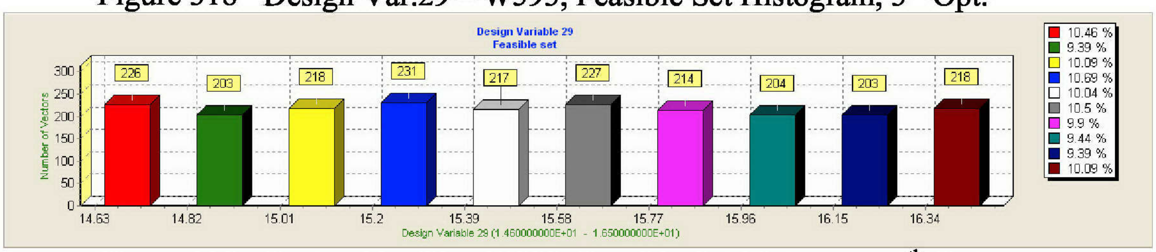

Figure 319 Design Var.29 – W593, Feasible Set Histogram, 4th Opt.

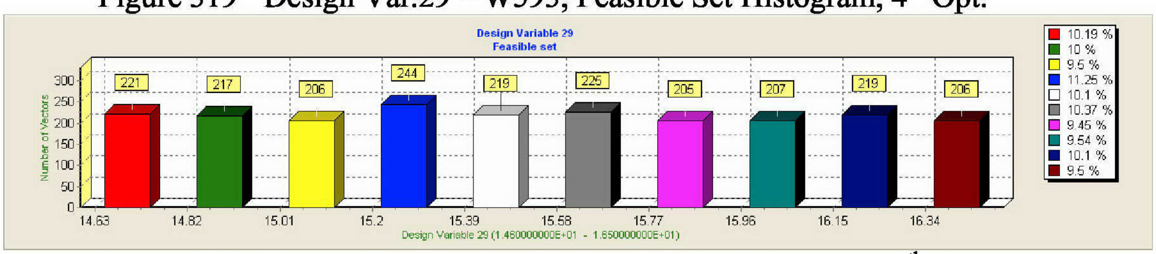

Figure 320 Design Var.29 – W593, Feasible Set Histogram, 5th Opt.

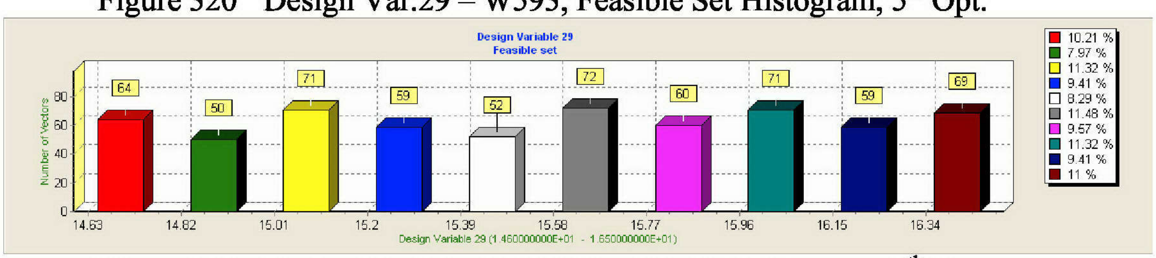

Figure 321 Design Var.29 – W593, Feasible Set Histogram, 6th Opt.

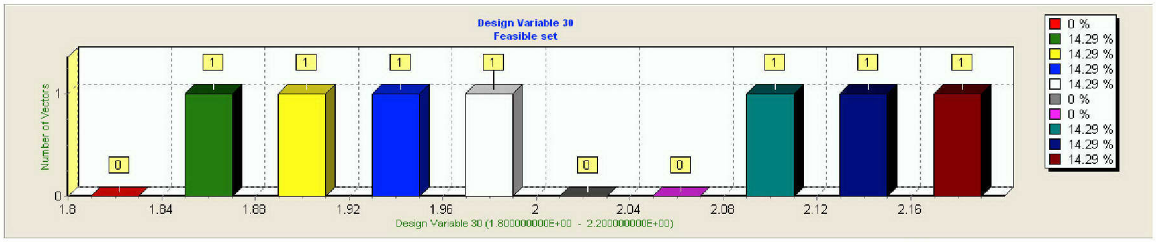

Figure 322 Design Var.30 – W171, Feasible Set Histogram, 1st Opt.

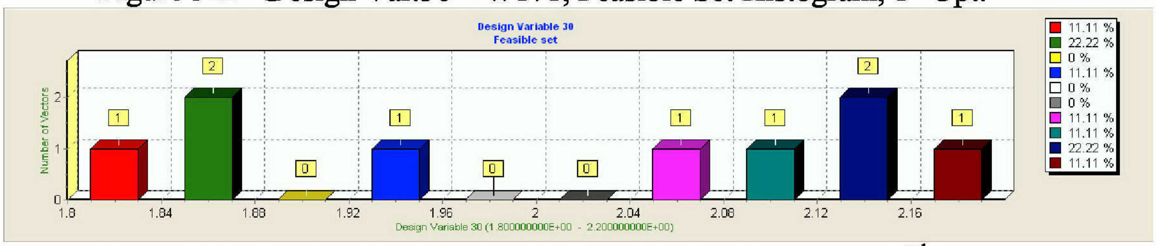

Figure 323 Design Var.30 – W171, Feasible Set Histogram, 2nd Opt.

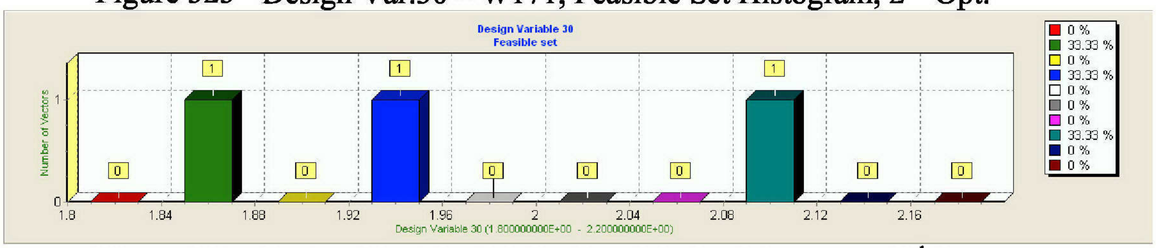

Figure 324 Design Var.30 – W171, Feasible Set Histogram, 3rd Opt.

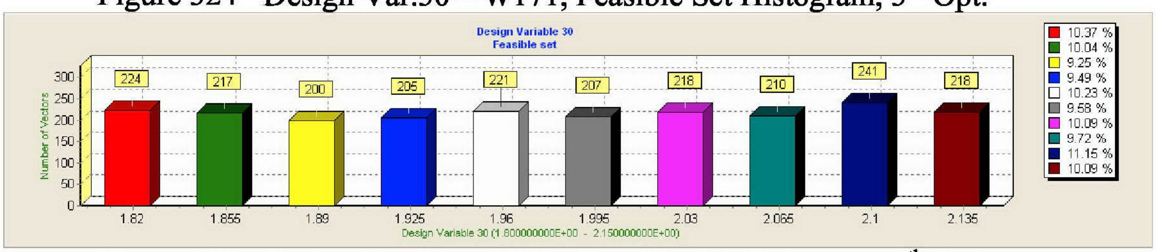

Figure 325 Design Var.30 – W171, Feasible Set Histogram, 4th Opt.

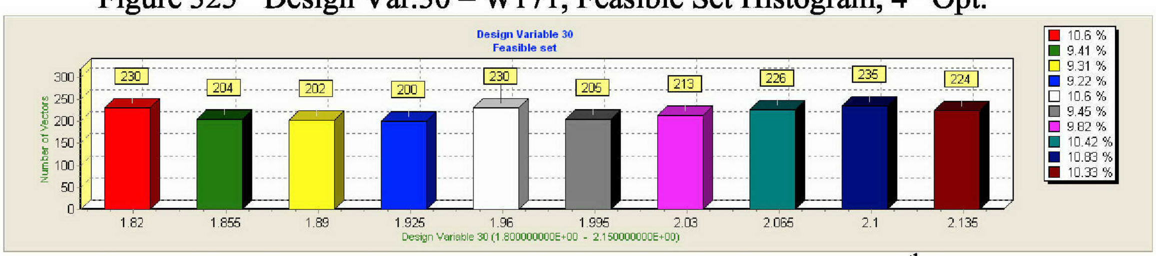

Figure 326 Design Var.30 – W171, Feasible Set Histogram, 5th Opt.

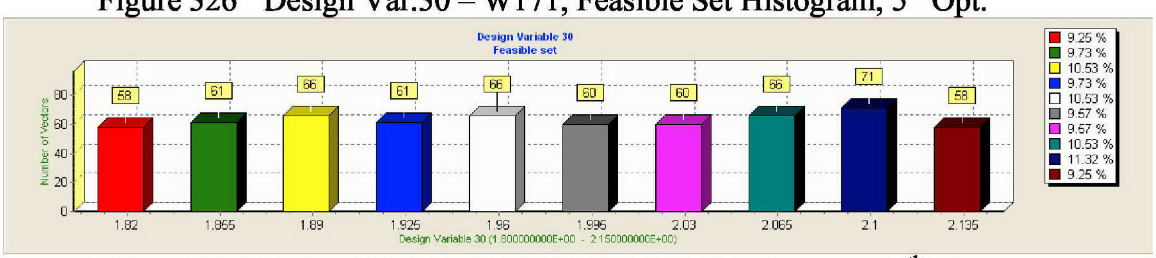

Figure 327 Design Var.30 – W171, Feasible Set Histogram, 6th Opt.

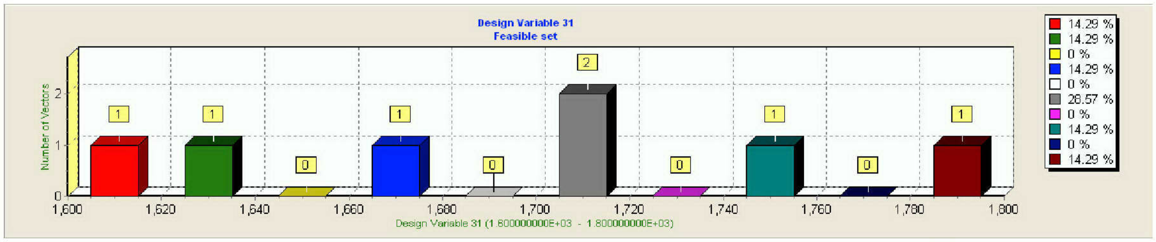

Figure 328 Design Var.31 – VWASTE, Feasible Set Histogram, 1st Opt.

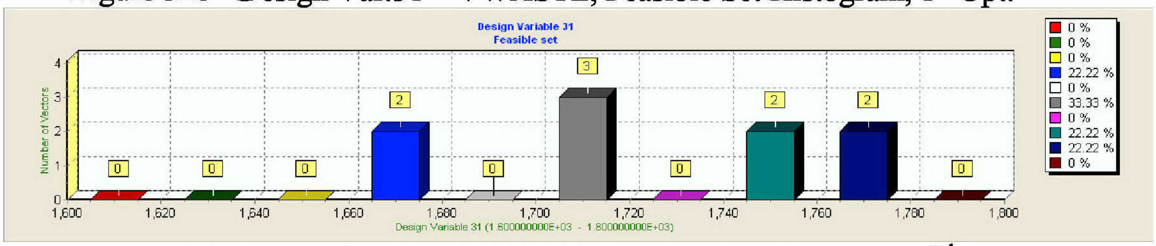

Figure 329 Design Var.31 – VWASTE, Feasible Set Histogram, 2nd Opt.

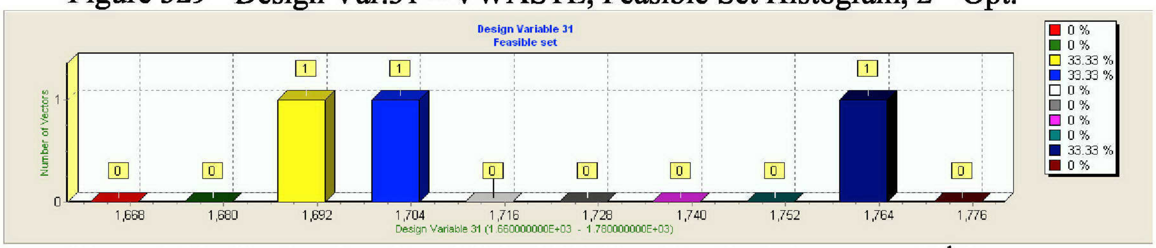

Figure 330 Design Var.31 – VWASTE, Feasible Set Histogram, 3rd Opt.

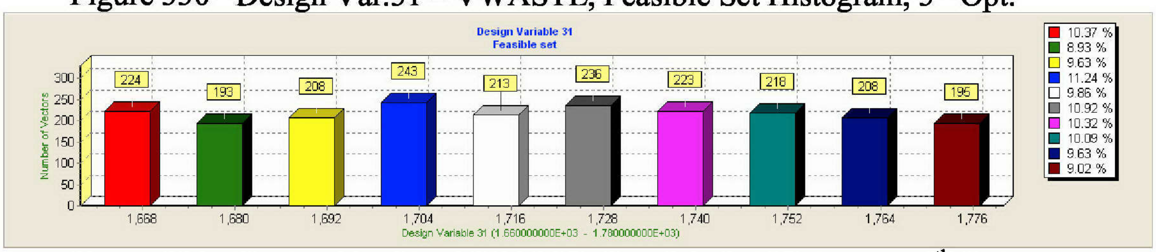

Figure 331 Design Var.31 – VWASTE, Feasible Set Histogram, 4th Opt.

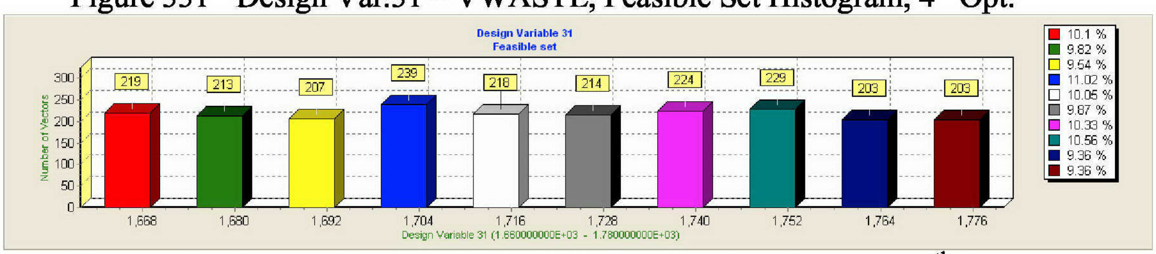

Figure 332 Design Var.31 – VWASTE, Feasible Set Histogram, 5th Opt.

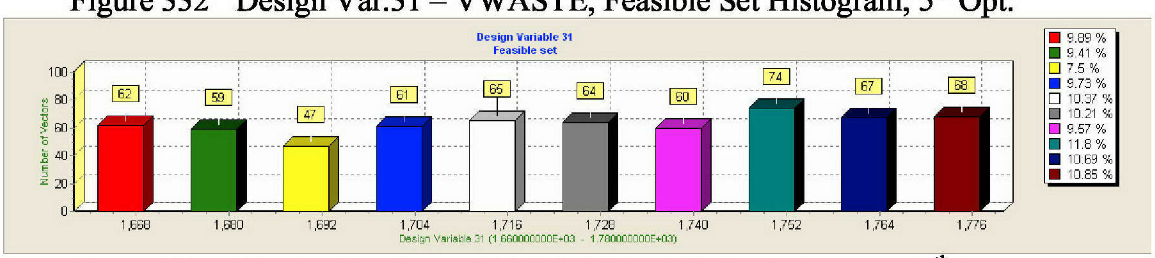

Figure 333 Design Var.31 – VWASTE, Feasible Set Histogram, 6th Opt.

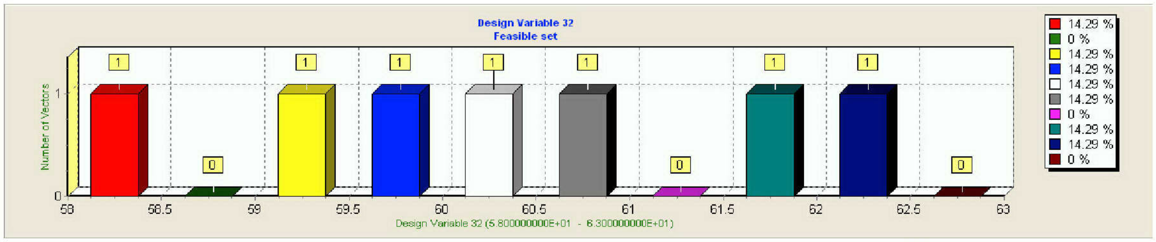

Figure 334 Design Var.32 – W598, Feasible Set Histogram, 1st Opt.

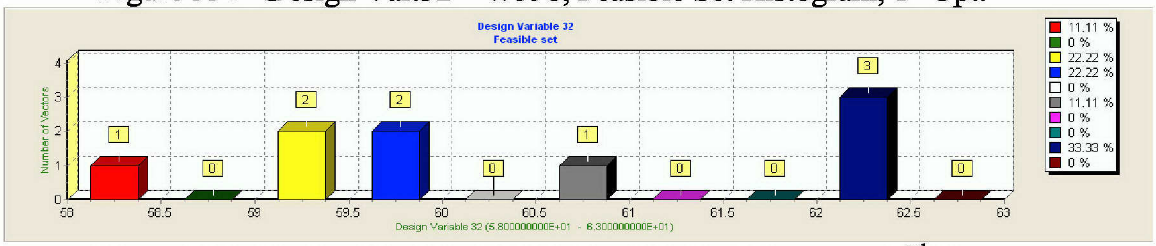

Figure 335 Design Var.32 – W598, Feasible Set Histogram, 2nd Opt.

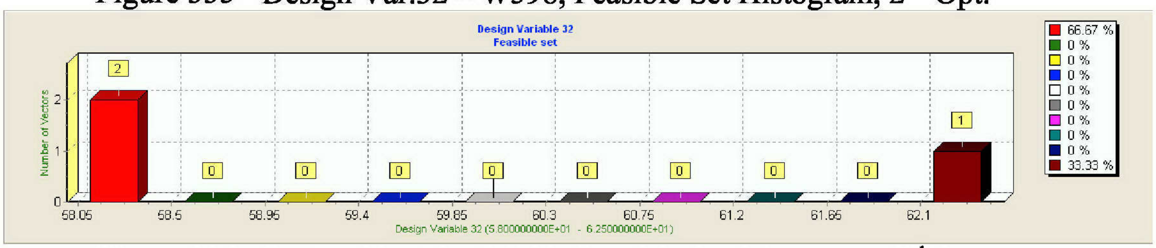

Figure 336 Design Var.32 – W598, Feasible Set Histogram, 3rd Opt.

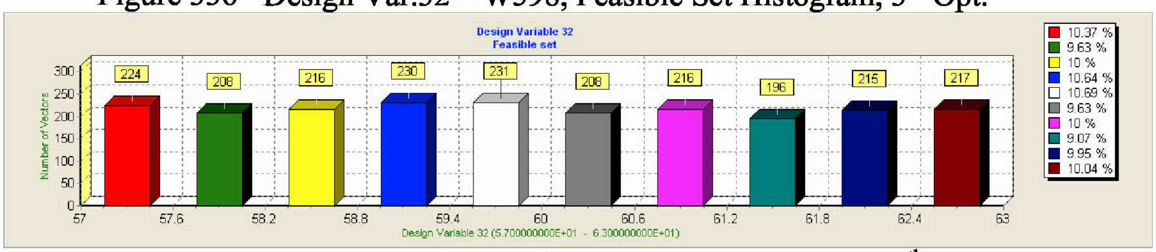

Figure 337 Design Var.32 – W598, Feasible Set Histogram, 4th Opt.

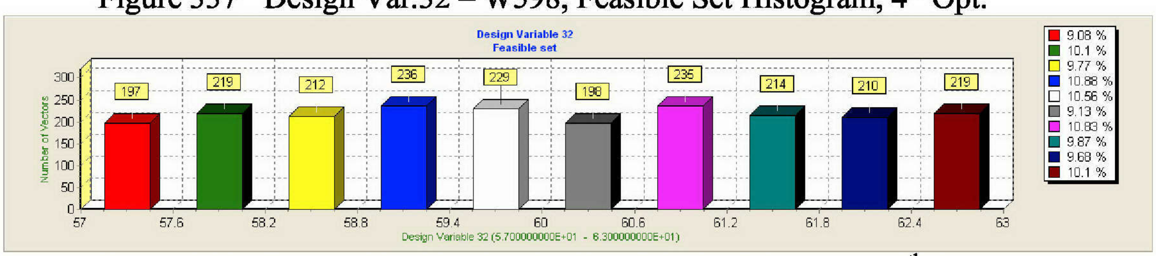

Figure 338 Design Var.32 – W598, Feasible Set Histogram, 5th Opt.

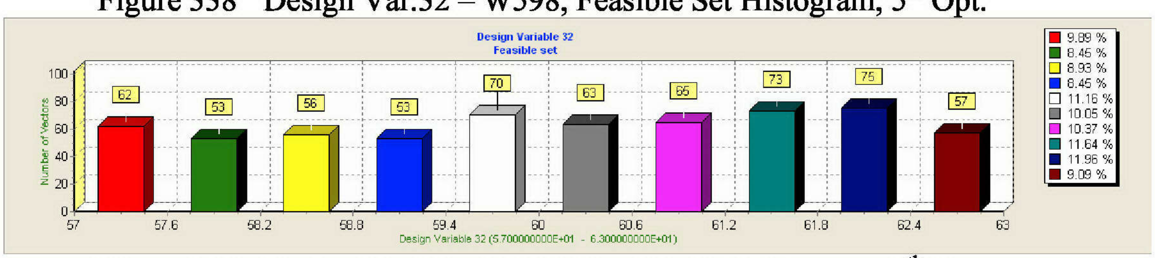

Figure 339 Design Var.32 – W598, Feasible Set Histogram, 6th Opt.

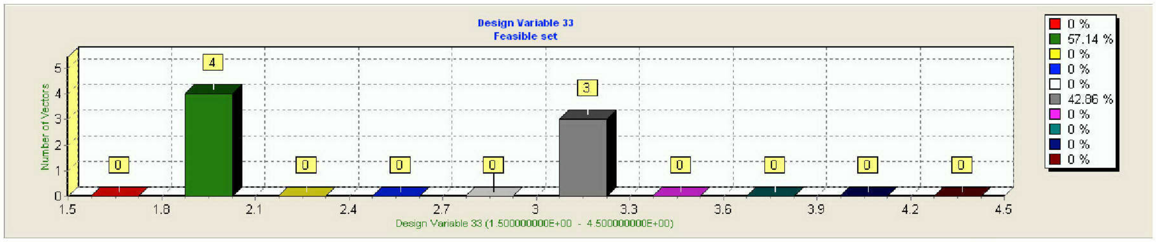

Figure 340 Design Var.33 – NG, DISCRETE, Feasible Set Histogram, 1st Opt.

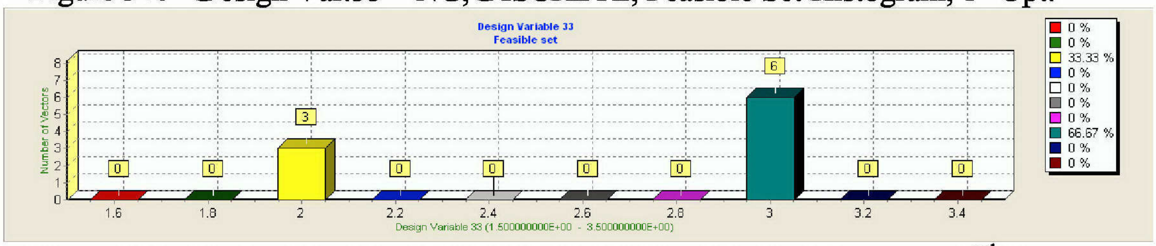

Figure 341 Design Var.33 – NG, DISCRETE, Feasible Set Histogram, 2nd Opt.

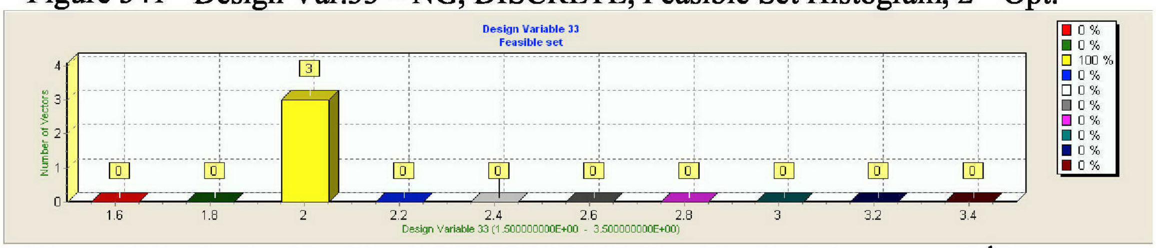

Figure 342 Design Var.33 – NG, DISCRETE, Feasible Set Histogram, 3rd Opt.

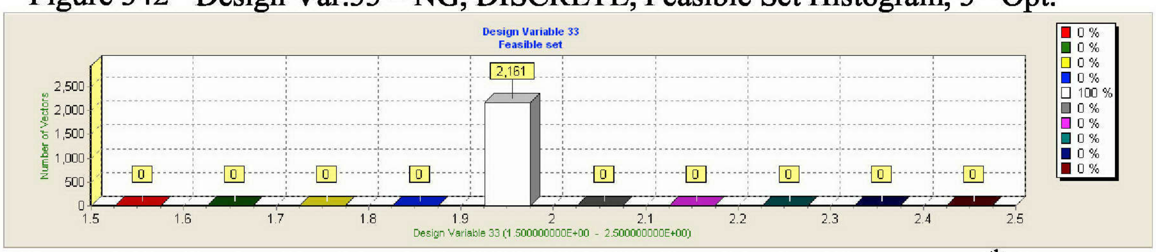

Figure 343 Design Var.33 – NG, **CONSTANT**, Feasible Set Histogram, 4th Opt.

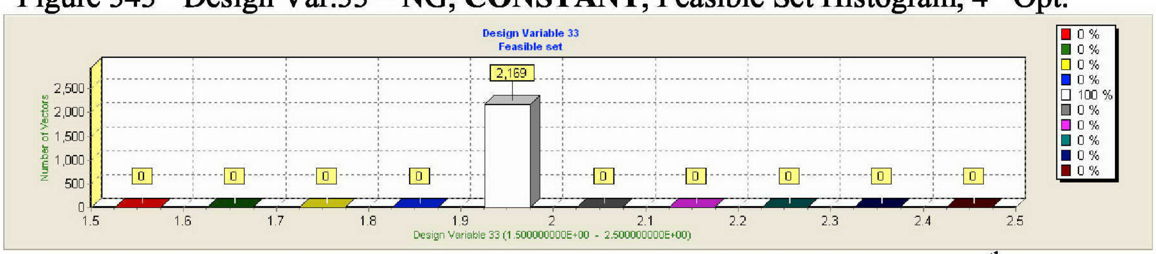

Figure 344 Design Var.33 – NG, **CONSTANT**, Feasible Set Histogram, 5th Opt.

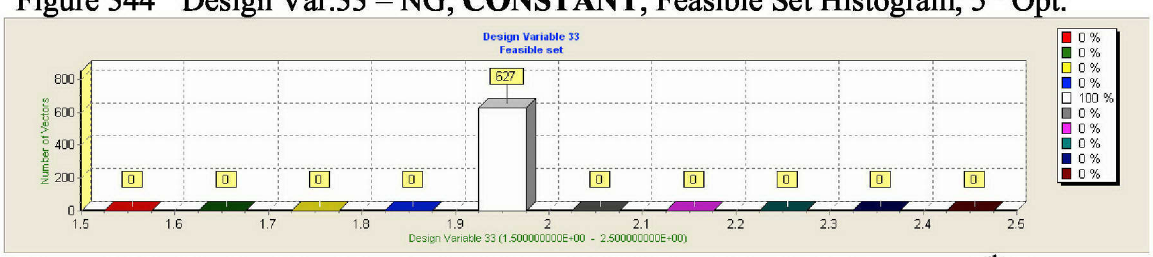

Figure 345 Design Var.33 – NG, **CONSTANT**, Feasible Set Histogram, 6th Opt.

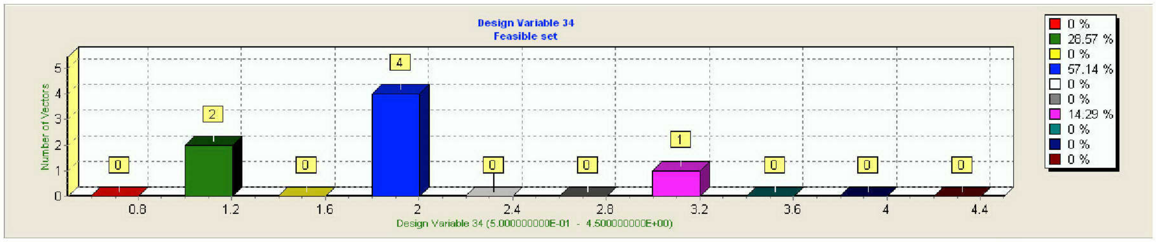

Figure 346 Design Var.34 – NHeIE, DISCRETE, Feasible Set Histogram, 1st Opt.

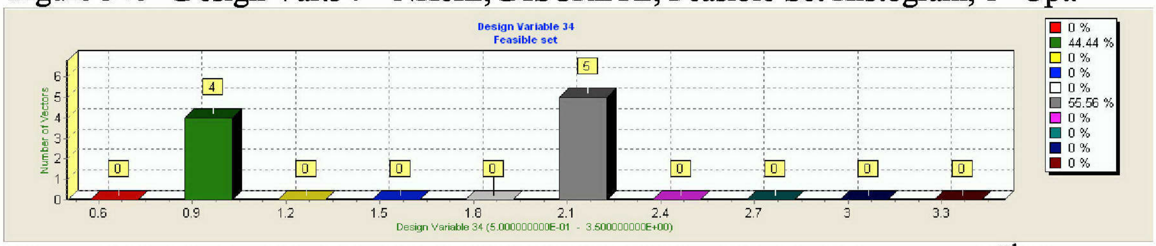

Figure 347 Design Var.34 – NHeIE, DISCRETE, Feasible Set Histogram, 2nd Opt.

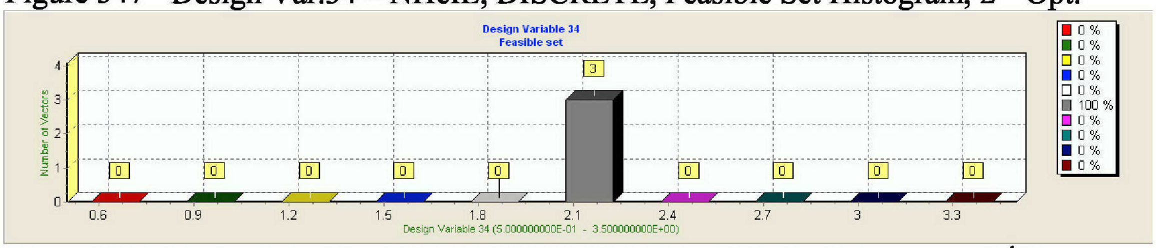

Figure 348 Design Var.34 – NHeIE, DISCRETE, Feasible Set Histogram, 3rd Opt.

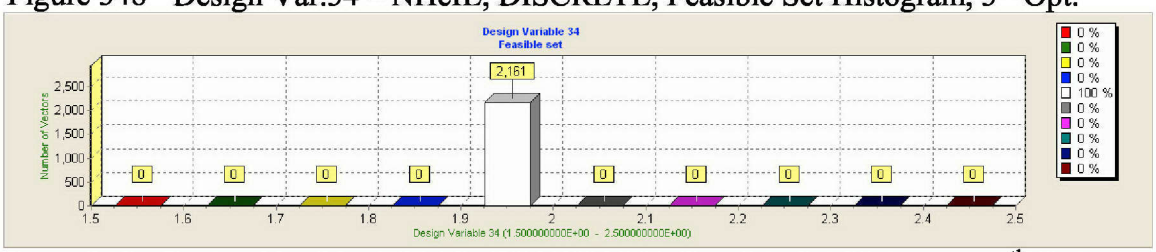

Figure 349 Design Var.34 – NHeIE, **CONSTANT**, Feasible Set Histogram, 4th Opt.

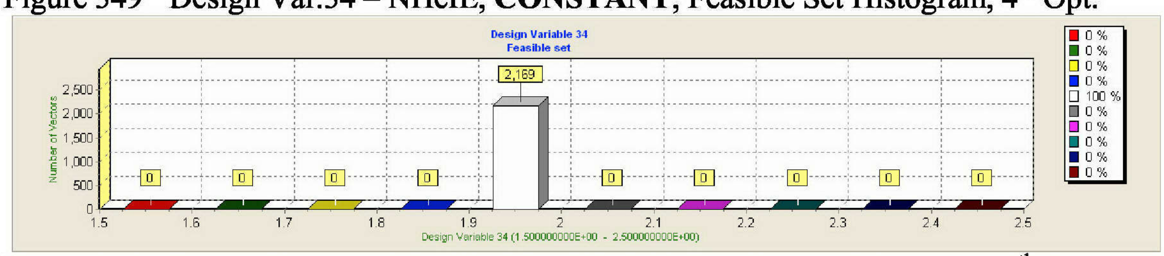

Figure 350 Design Var.34 – NHeIE, **CONSTANT**, Feasible Set Histogram, 5th Opt.

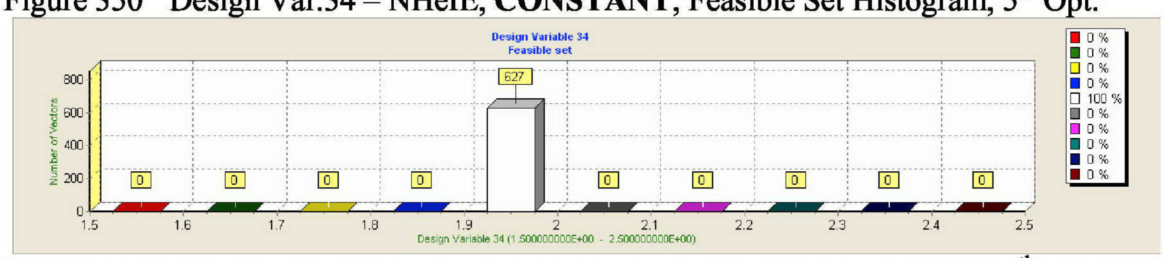

Figure 351 Design Var.34 – NHeIE, **CONSTANT**, Feasible Set Histogram, 6th Opt.

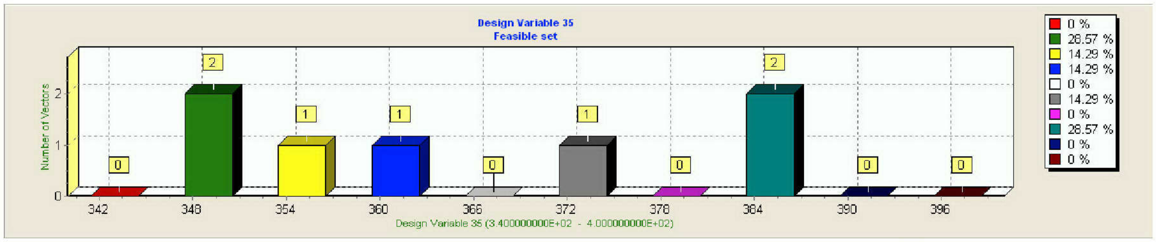

Figure 352 Design Var.35 – WBP, Feasible Set Histogram, 1st Opt.

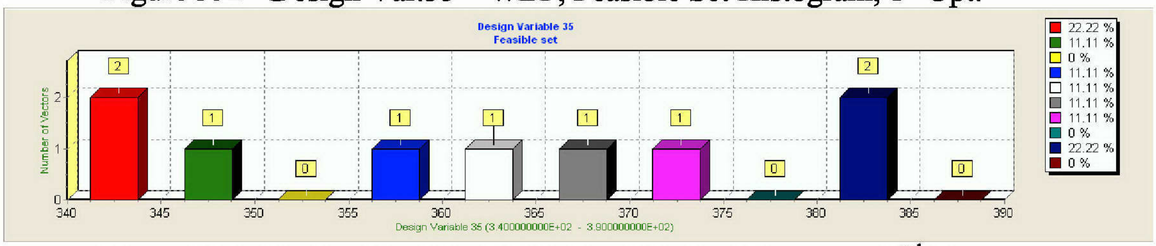

Figure 353 Design Var.35 – WBP, Feasible Set Histogram, 2nd Opt.

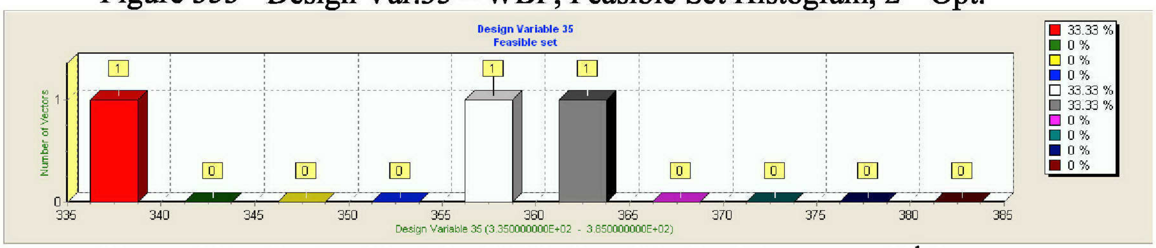

Figure 354 Design Var.35 – WBP, Feasible Set Histogram, 3rd Opt.

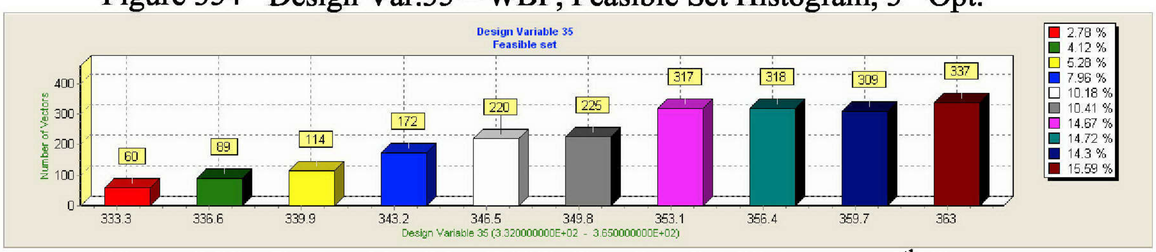

Figure 355 Design Var.35 – WBP, Feasible Set Histogram, 4th Opt.

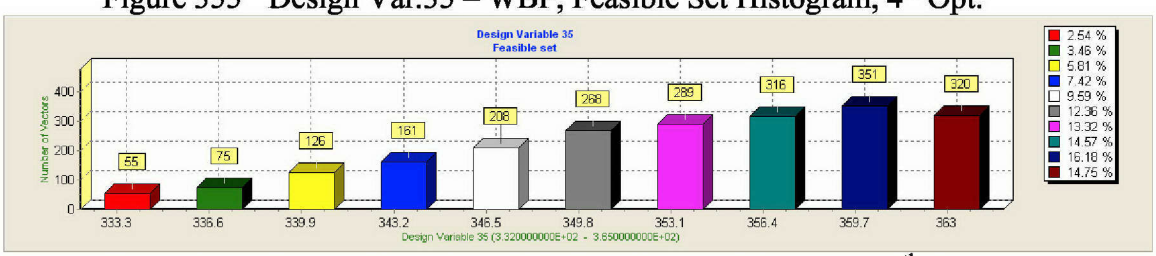

Figure 356 Design Var.35 – WBP, Feasible Set Histogram, 5th Opt.

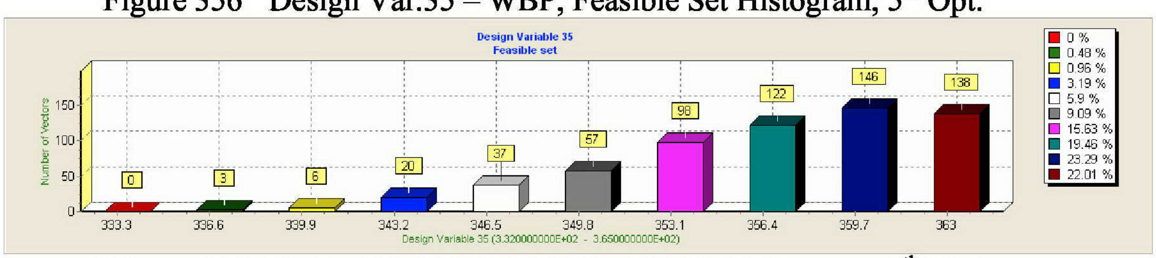

Figure 357 Design Var.35 – WBP, Feasible Set Histogram, 6th Opt.

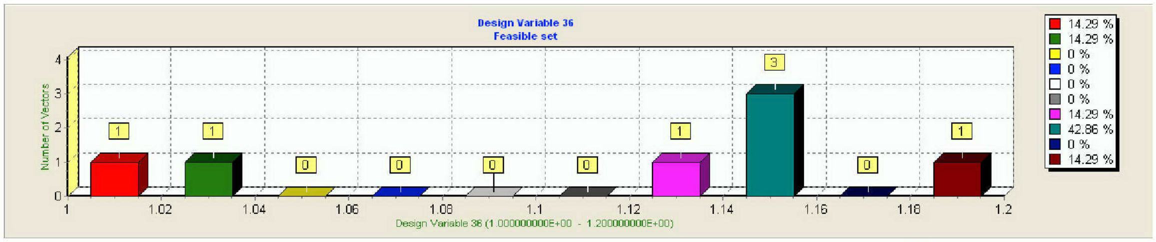

Figure 358 Design Var.36 – D10C, Feasible Set Histogram, 1st Opt.

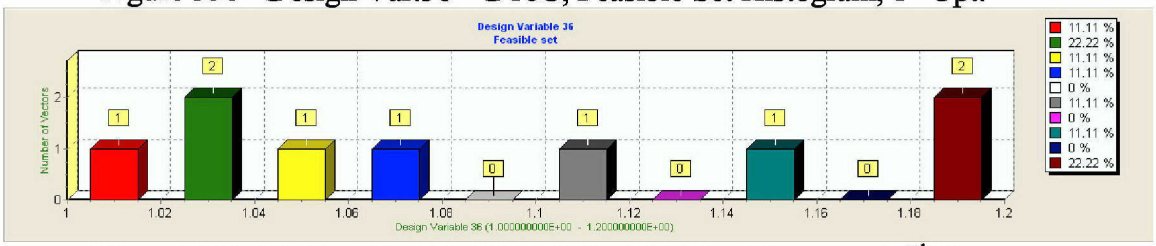

Figure 359 Design Var.36 – D10C, Feasible Set Histogram, 2nd Opt.

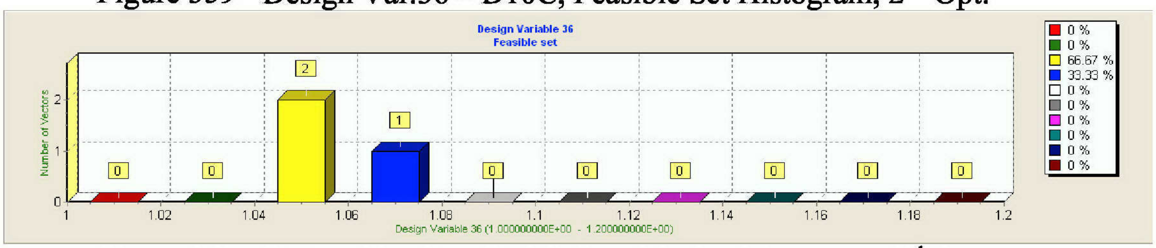

Figure 360 Design Var.36 – D10C, Feasible Set Histogram, 3rd Opt.

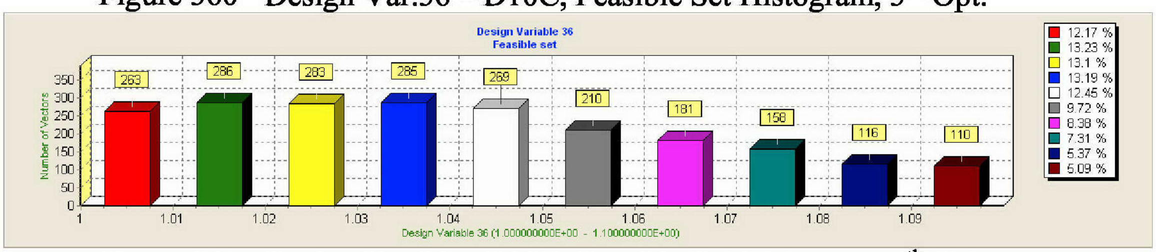

Figure 361 Design Var.36 – D10C, Feasible Set Histogram, 4th Opt.

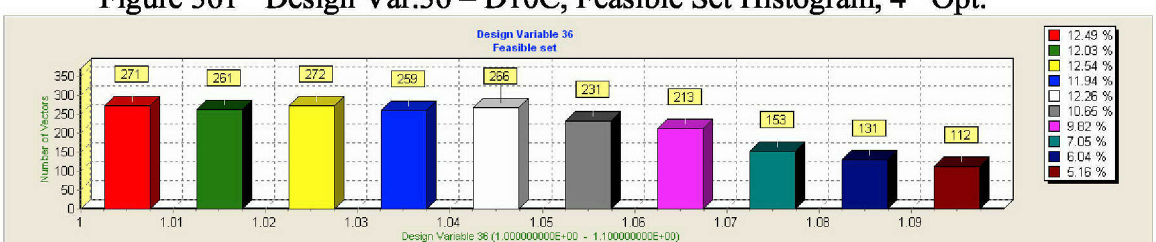

Figure 362 Design Var.36 – D10C, Feasible Set Histogram, 5th Opt.

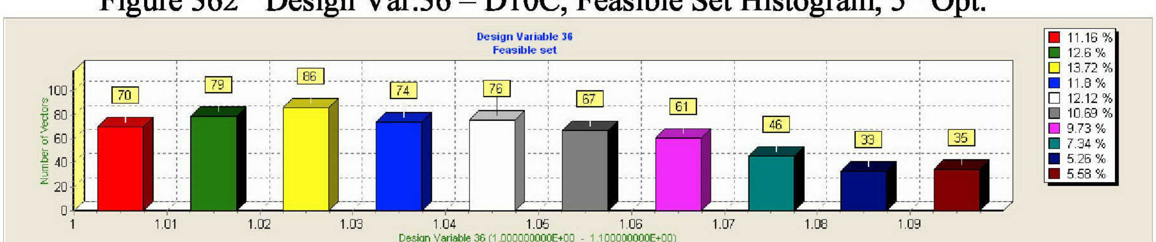

Figure 363 Design Var.36 – D10C, Feasible Set Histogram, 6th Opt.

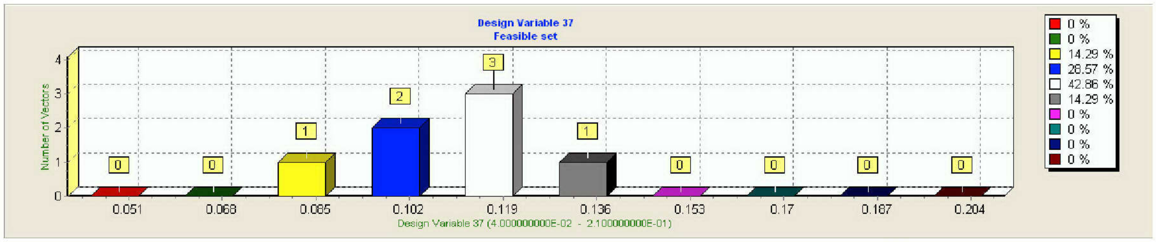

Figure 364 Design Var.37 – FP, Feasible Set Histogram, 1st Opt.

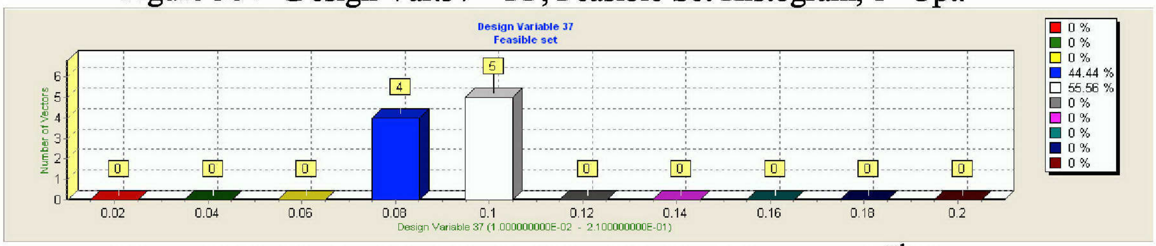

Figure 365 Design Var.37 – FP, Feasible Set Histogram, 2nd Opt.

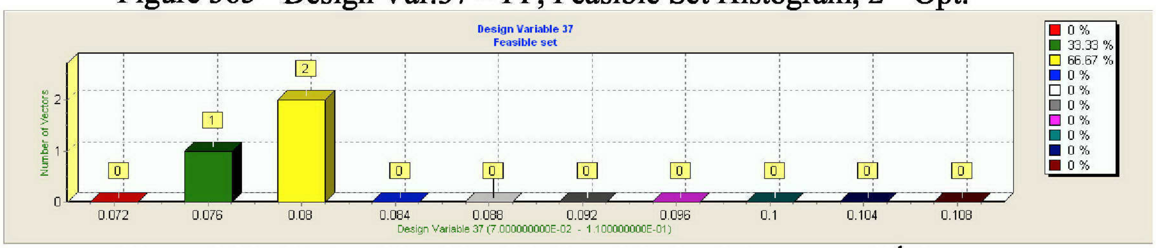

Figure 366 Design Var.37 – FP, Feasible Set Histogram, 3rd Opt.

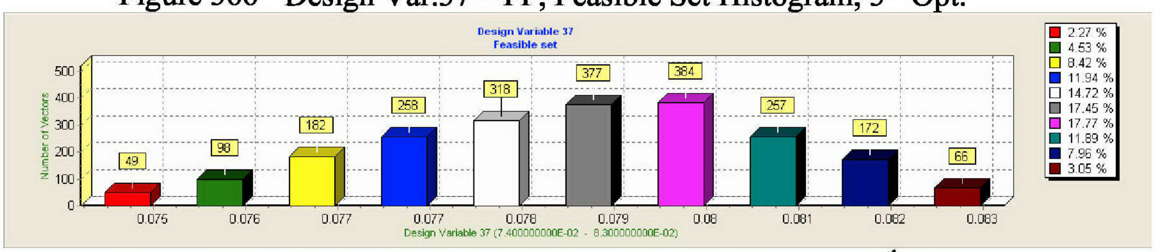

Figure 367 Design Var.37 – FP, Feasible Set Histogram, 4th Opt.

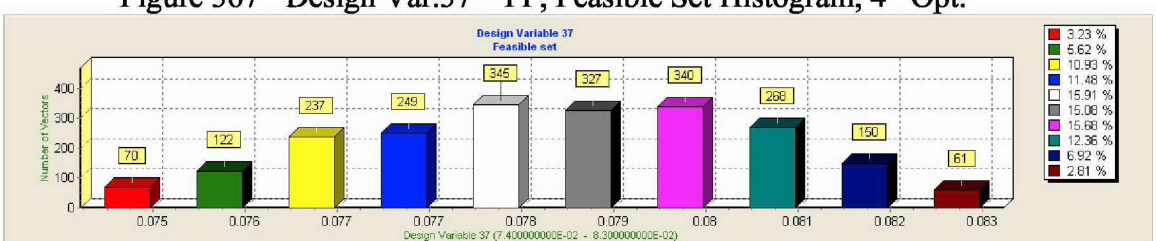

Figure 368 Design Var.37 – FP, Feasible Set Histogram, 5th Opt.

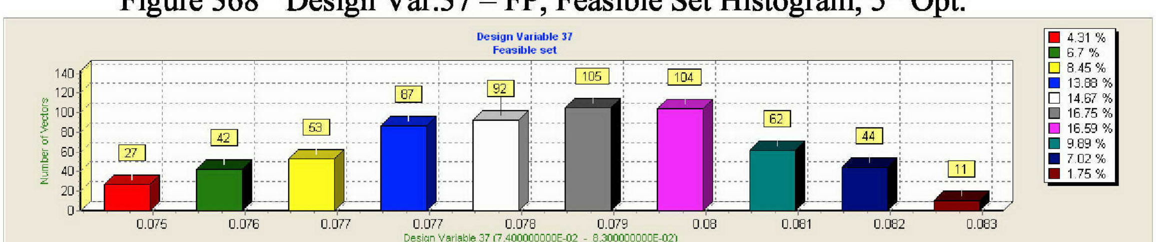

Figure 369 Design Var.37 – FP, Feasible Set Histogram, 6th Opt.

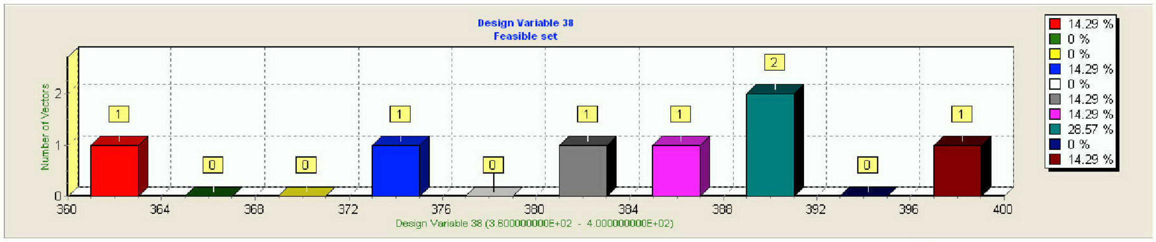

Figure 370 Design Var.38 – WOFH, Feasible Set Histogram, 1st Opt.

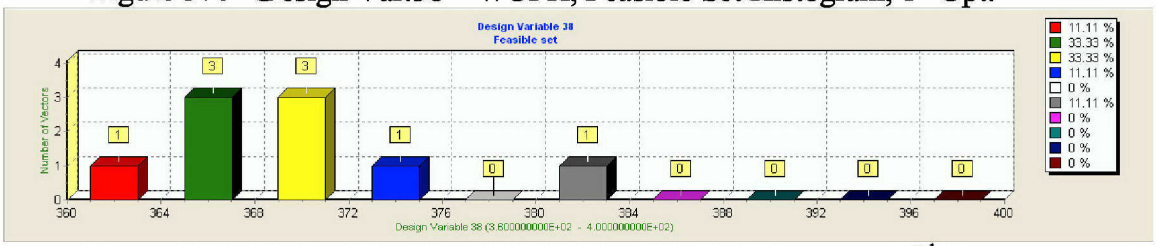

Figure 371 Design Var.38 – WOFH, Feasible Set Histogram, 2nd Opt.

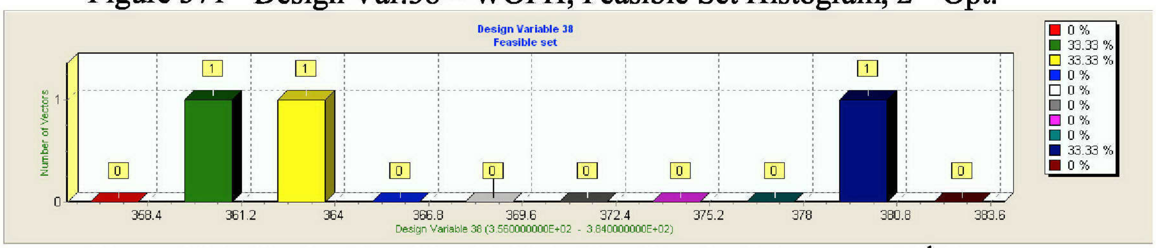

Figure 372 Design Var.38 – WOFH, Feasible Set Histogram, 3rd Opt.

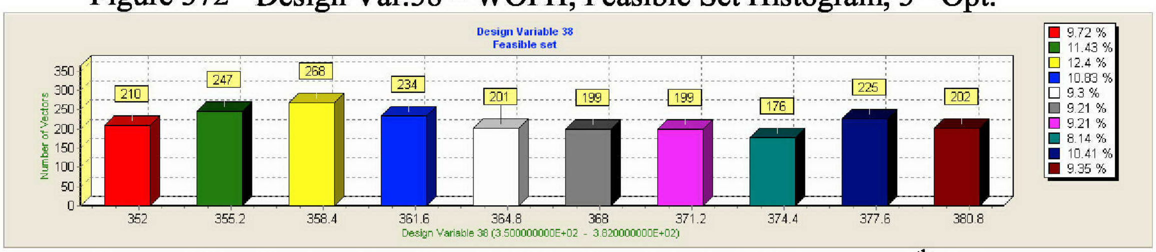

Figure 373 Design Var.38 – WOFH, Feasible Set Histogram, 4th Opt.

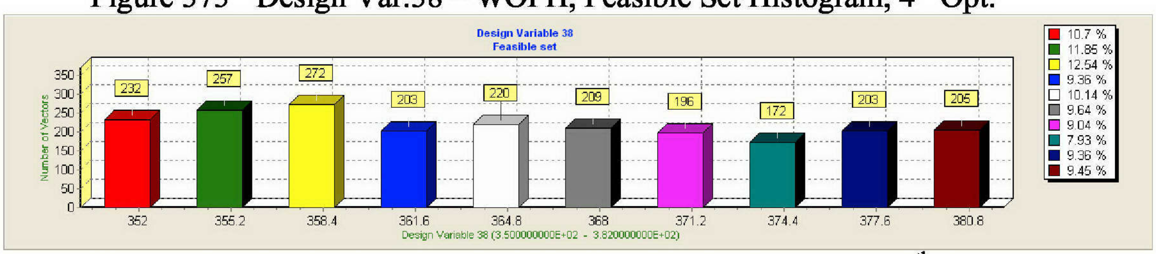

Figure 374 Design Var.38 – WOFH, Feasible Set Histogram, 5th Opt.

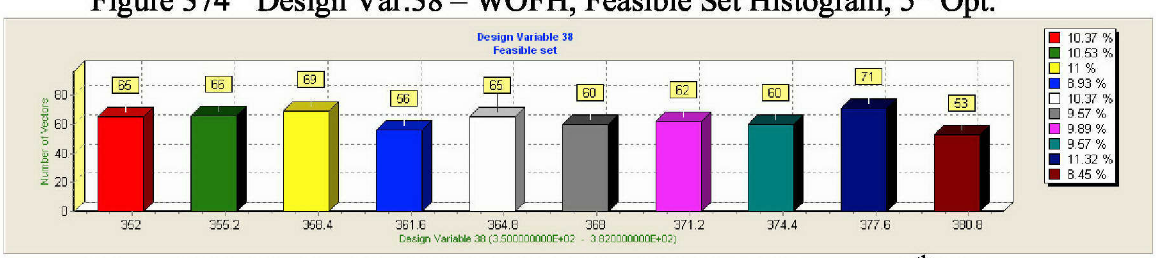

Figure 375 Design Var.38 – WOFH, Feasible Set Histogram, 6th Opt.

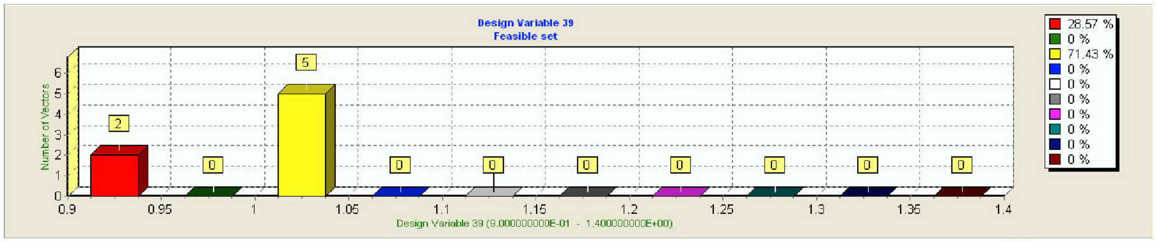

Figure 376 Design Var.39 – CHMAT, DISCRETE, Feasible Set Histogram, 1st Opt.

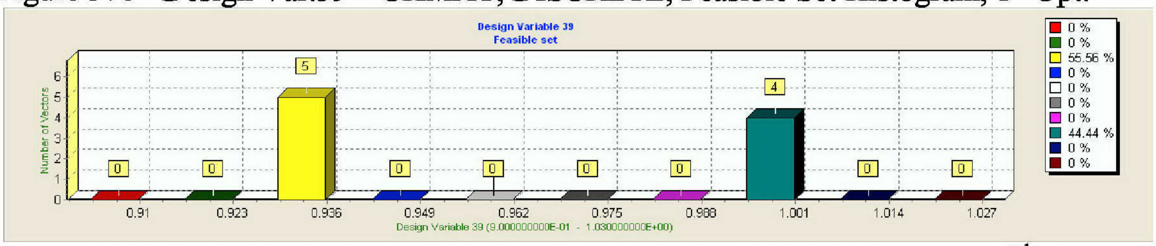

Figure 377 Design Var.39 – CHMAT, DISCRETE, Feasible Set Histogram, 2nd Opt.

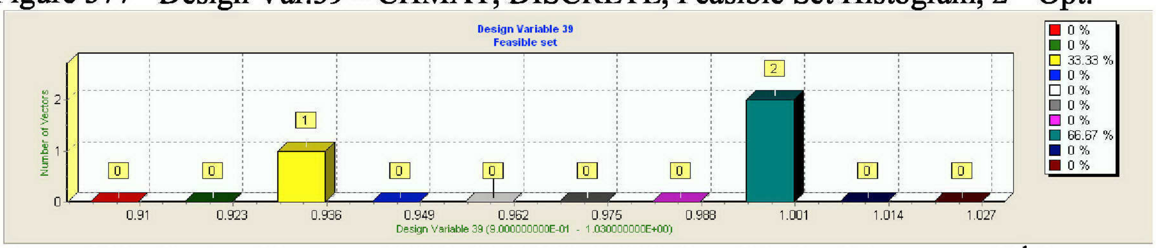

Figure 378 Design Var.39 – CHMAT, DISCRETE, Feasible Set Histogram, 3rd Opt.

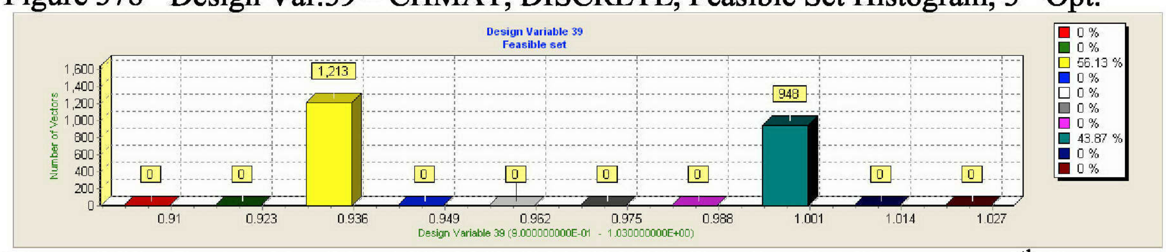

Figure 379 Design Var.39 – CHMAT, DISCRETE, Feasible Set Histogram, 4th Opt.

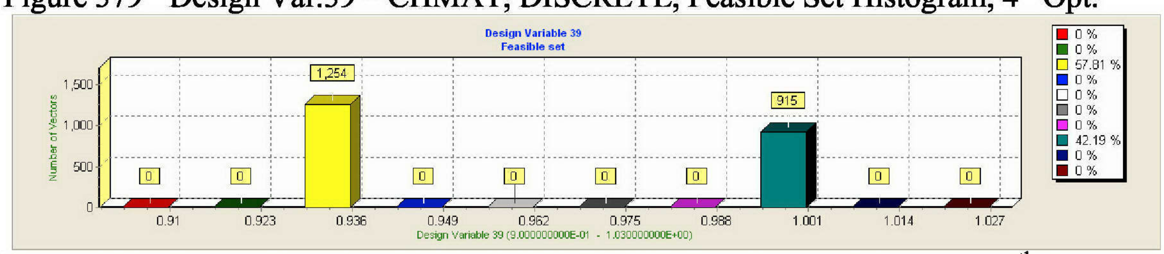

Figure 380 Design Var.39 – CHMAT, DISCRETE, Feasible Set Histogram, 5th Opt.

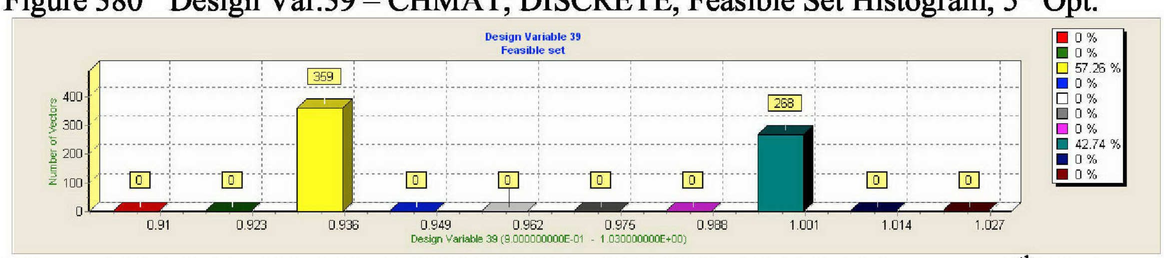

Figure 381 Design Var.39 – CHMAT, DISCRETE, Feasible Set Histogram, 6th Opt.

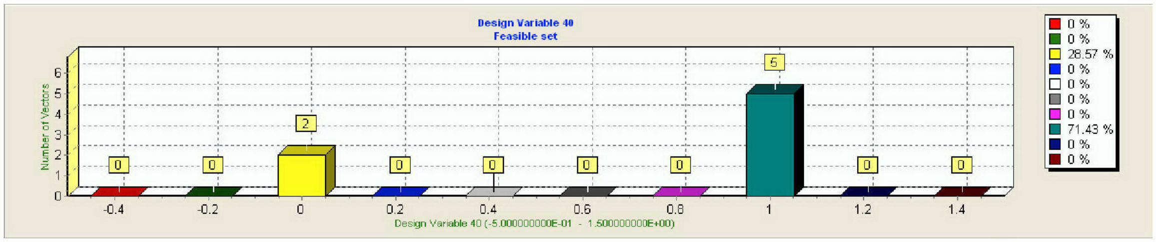

Figure 382 Design Var.40 – CBVC, DISCRETE, Feasible Set Histogram, 1st Opt.

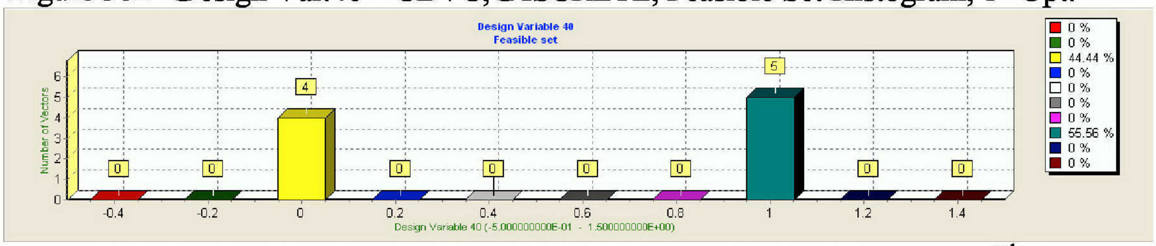

Figure 383 Design Var.40 – CBVC, DISCRETE, Feasible Set Histogram, 2nd Opt.

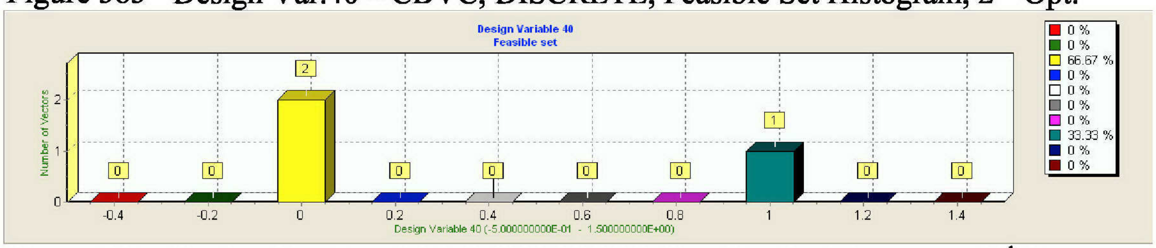

Figure 384 Design Var.40 – CBVC, DISCRETE, Feasible Set Histogram, 3rd Opt.

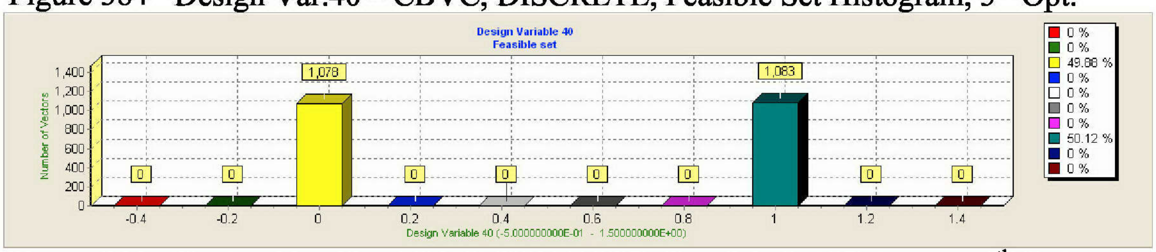

Figure 385 Design Var.40 – CBVC, DISCRETE, Feasible Set Histogram, 4th Opt.

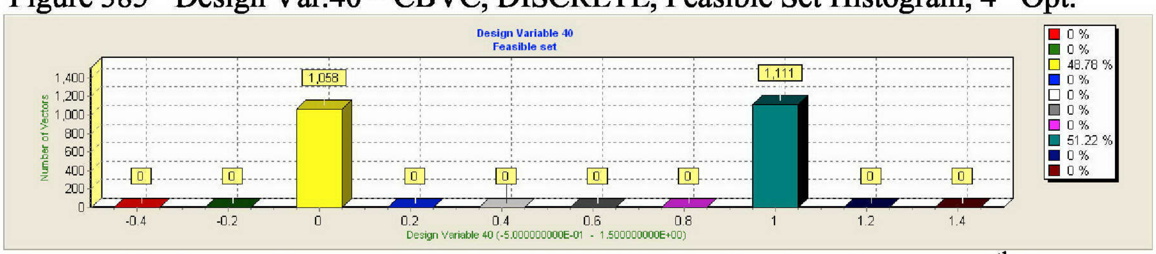

Figure 386 Design Var.40 – CBVC, DISCRETE, Feasible Set Histogram, 5th Opt.

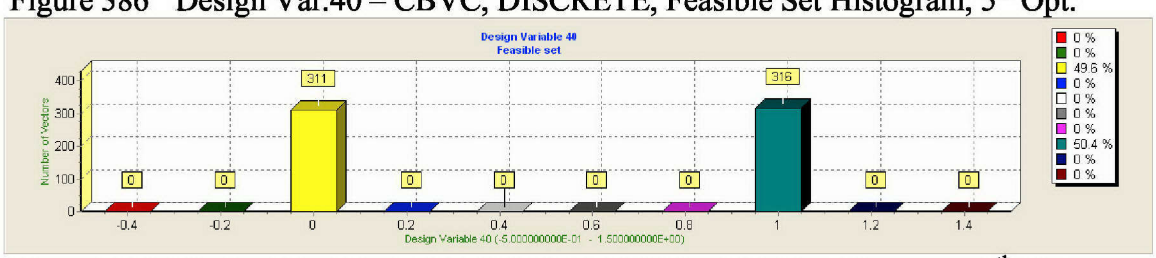

Figure 387 Design Var.40 – CBVC, DISCRETE, Feasible Set Histogram, 6th Opt.

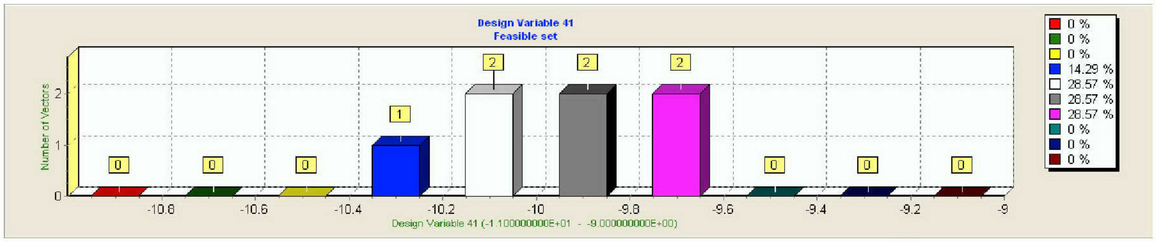

Figure 388 Design Var.41 – LCB, Feasible Set Histogram, 1st Opt.

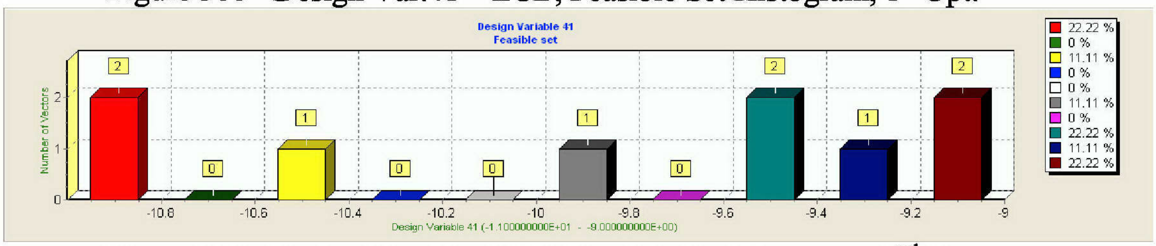

Figure 389 Design Var.41 – LCB, Feasible Set Histogram, 2nd Opt.

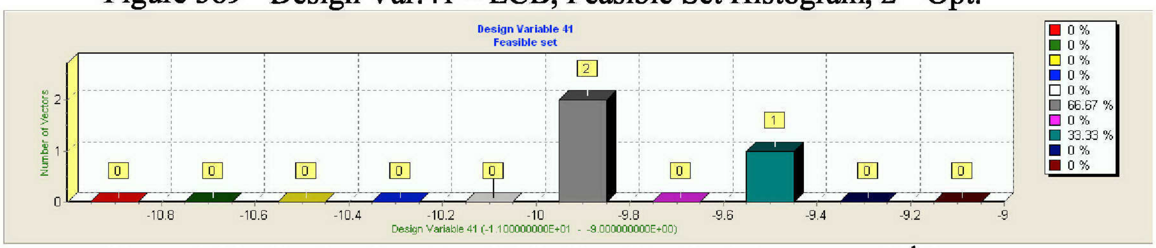

Figure 390 Design Var.41 – LCB, Feasible Set Histogram, 3rd Opt.

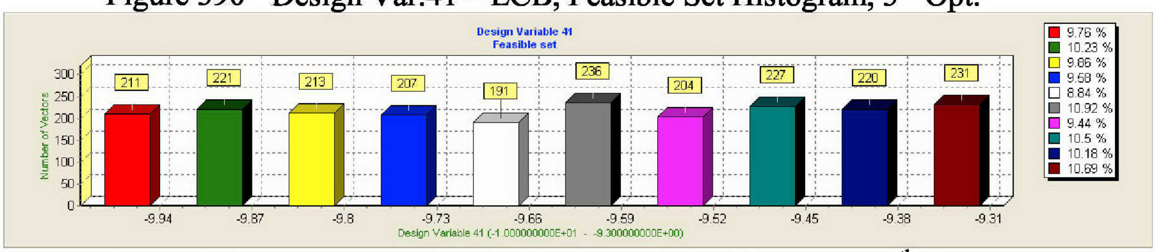

Figure 391 Design Var.41 – LCB, Feasible Set Histogram, 4th Opt.

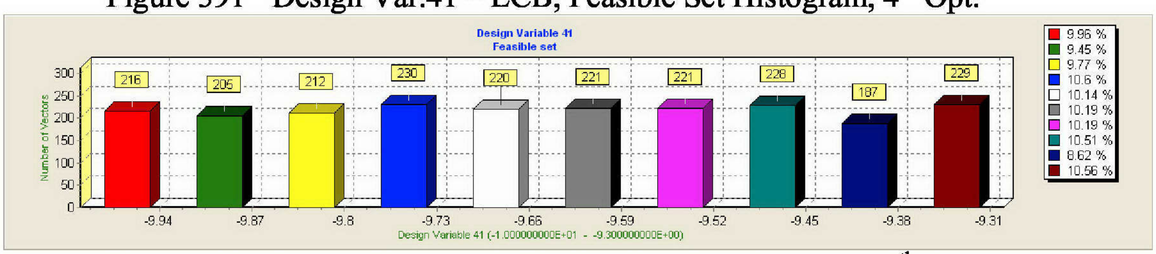

Figure 392 Design Var.41 – LCB, Feasible Set Histogram, 5th Opt.

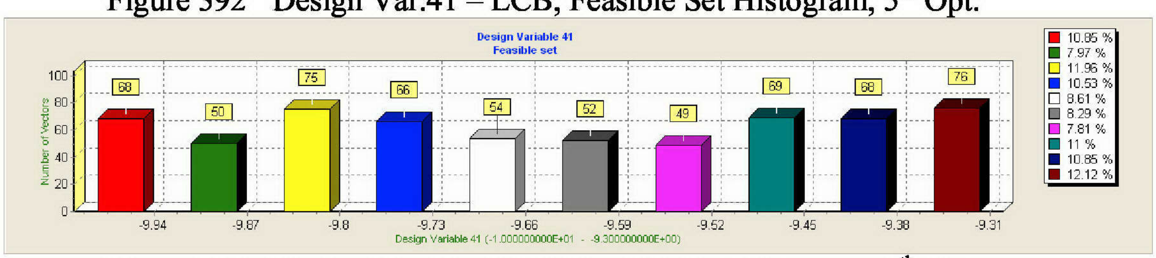

Figure 393 Design Var.41 – LCB, Feasible Set Histogram, 6th Opt.

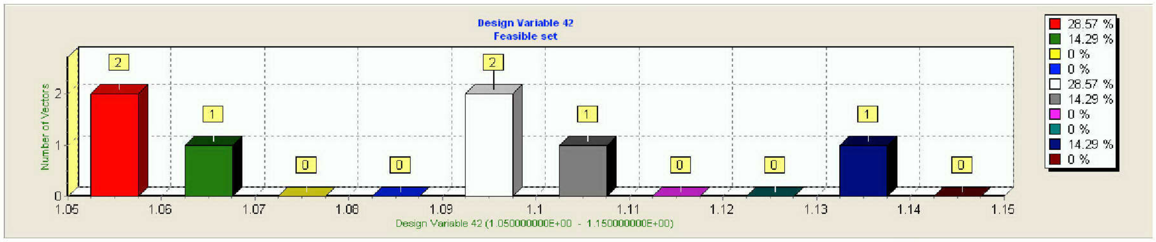

Figure 394 Design Var.42 – PMF, Feasible Set Histogram, 1st Opt.

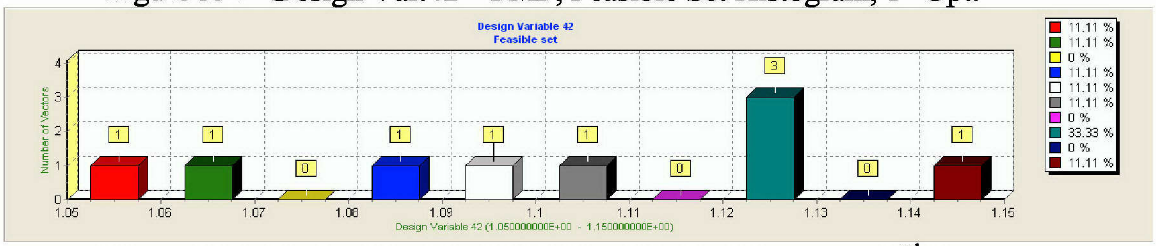

Figure 395 Design Var.42 – PMF, Feasible Set Histogram, 2nd Opt.

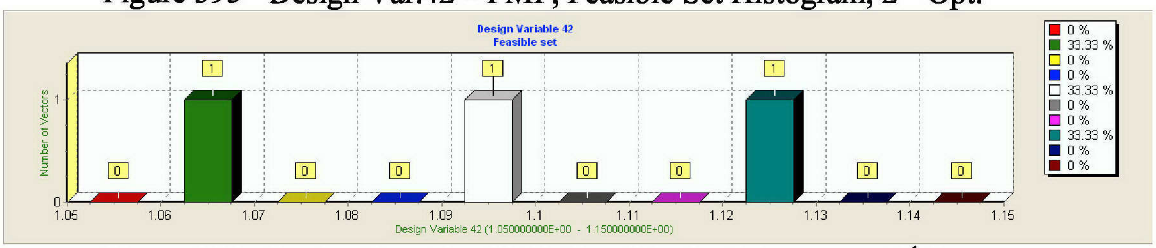

Figure 396 Design Var.42 – PMF, Feasible Set Histogram, 3rd Opt.

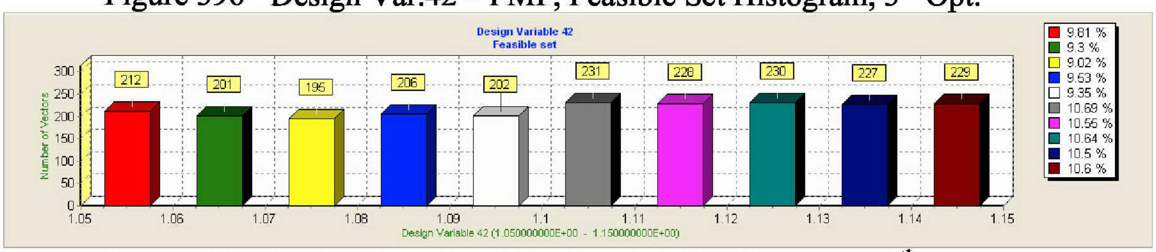

Figure 397 Design Var.42 – PMF, Feasible Set Histogram, 4th Opt.

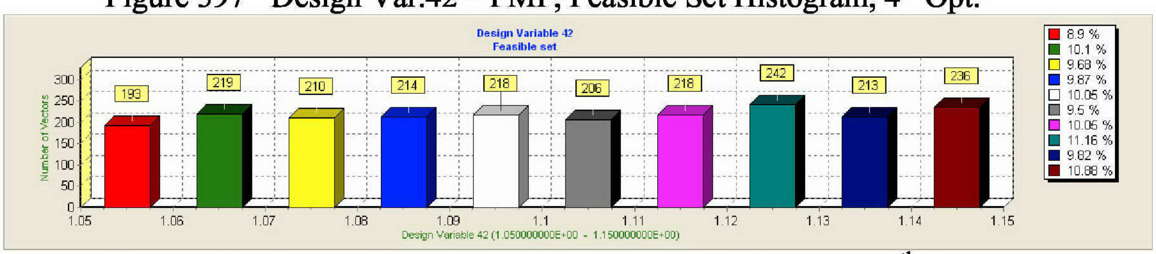

Figure 398 Design Var.42 – PMF, Feasible Set Histogram, 5th Opt.

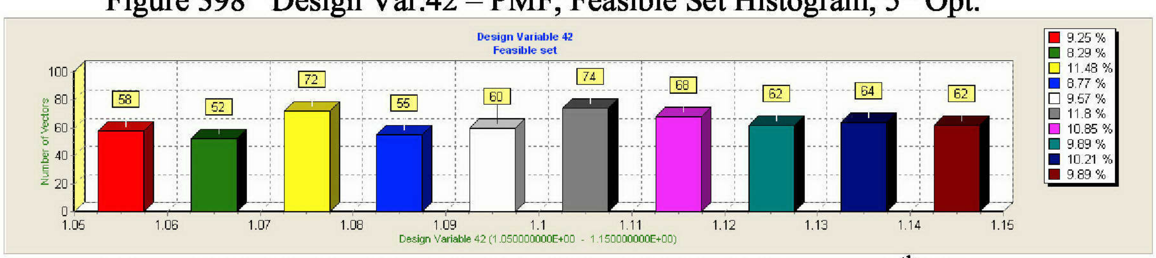

Figure 399 Design Var.42 – PMF, Feasible Set Histogram, 6th Opt.

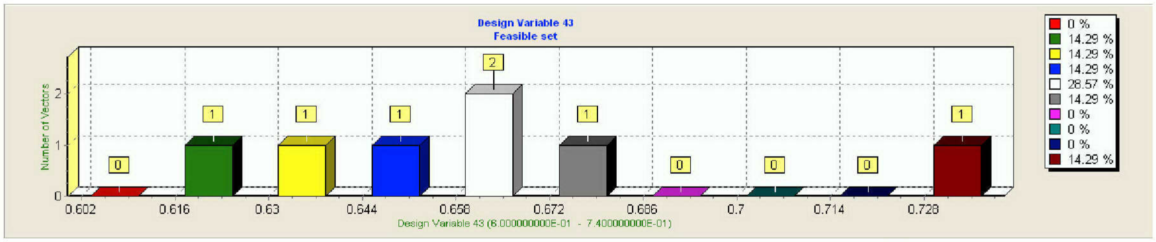

Figure 400 Design Var.43 – PC, Feasible Set Histogram, 1st Opt.

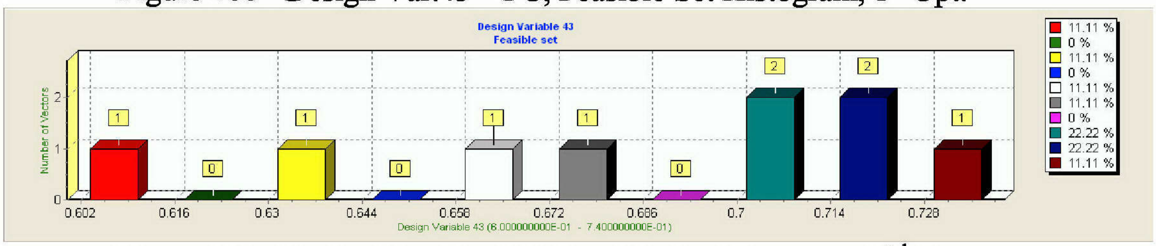

Figure 401 Design Var.43 – PC, Feasible Set Histogram, 2nd Opt.

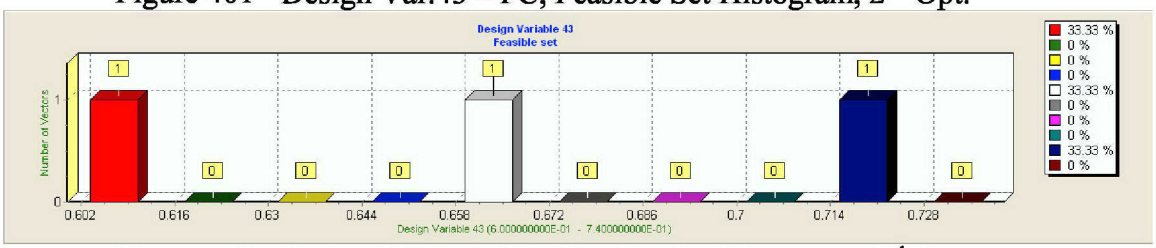

Figure 402 Design Var.43 – PC, Feasible Set Histogram, 3rd Opt.

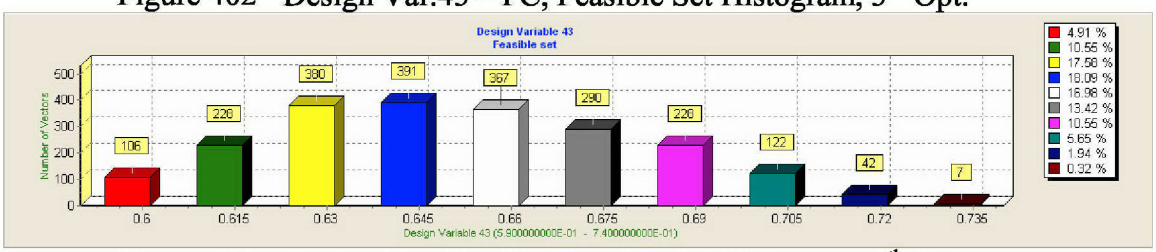

Figure 403 Design Var.43 – PC, Feasible Set Histogram, 4th Opt.

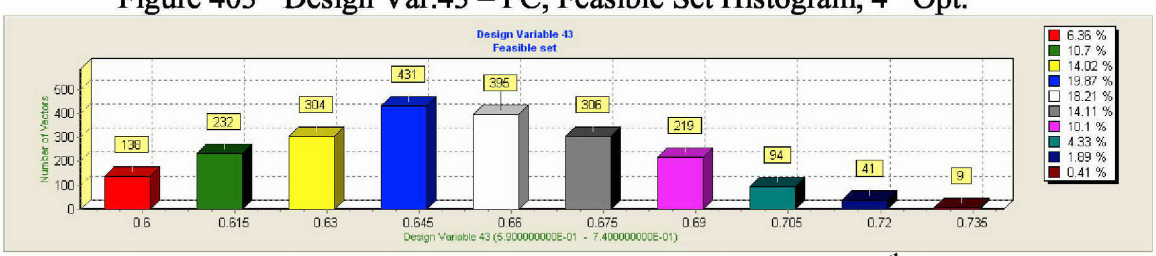

Figure 404 Design Var.43 – PC, Feasible Set Histogram, 5th Opt.

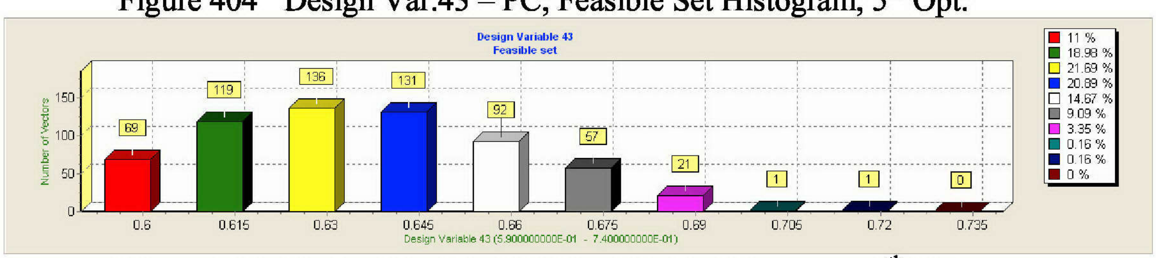

Figure 405 Design Var.43 – PC, Feasible Set Histogram, 6th Opt.

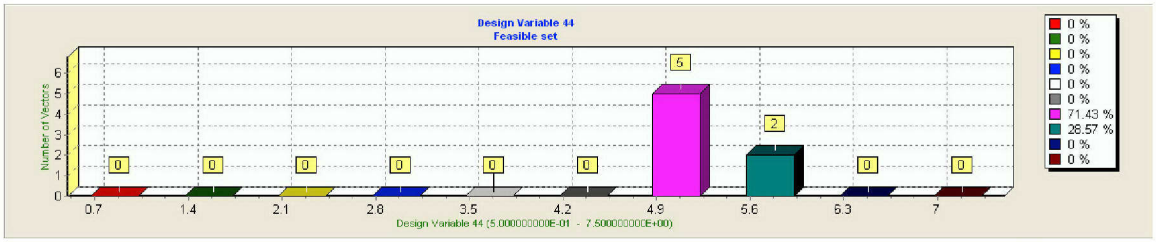

Figure 406 Design Var.44 – SELECTP, DISCRETE, Feasible Set Histogram, 1st Opt.

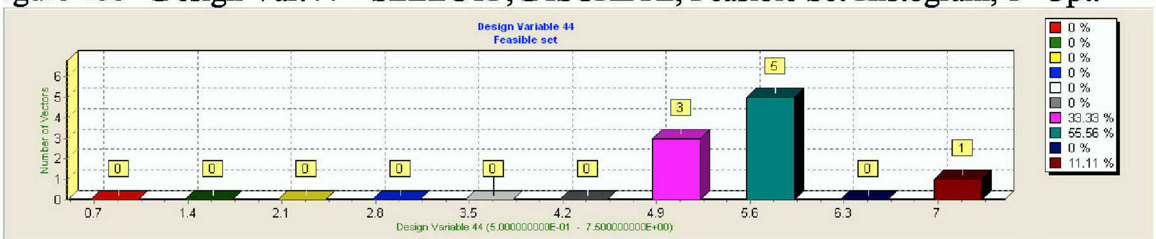

Figure 407 Design Var.44 – SELECTP, DISCRETE, Feasible Set Histogram, 2nd Opt.

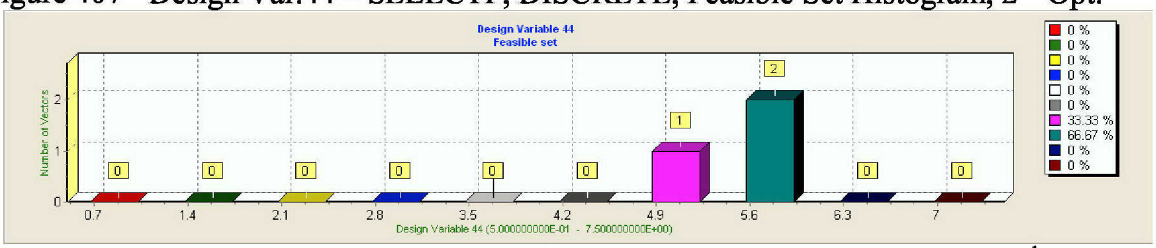

Figure 408 Design Var.44 – SELECTP, DISCRETE, Feasible Set Histogram, 3rd Opt.

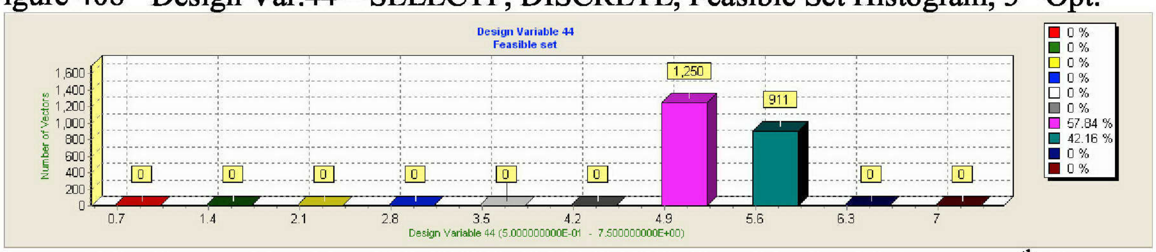

Figure 409 Design Var.44 – SELECTP, DISCRETE, Feasible Set Histogram, 4th Opt.

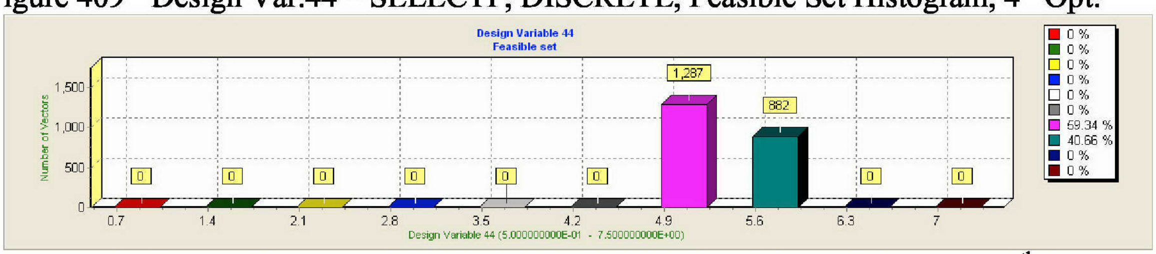

Figure 410 Design Var.44 – SELECTP, DISCRETE, Feasible Set Histogram, 5th Opt.

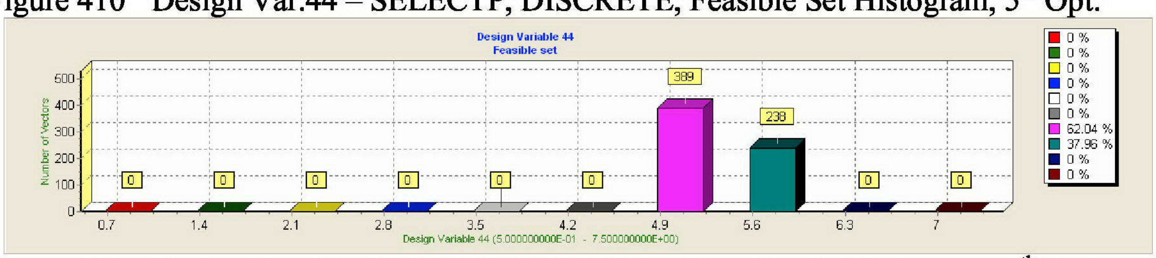

Figure 411 Design Var.44 – SELECTP, DISCRETE, Feasible Set Histogram, 6th Opt.

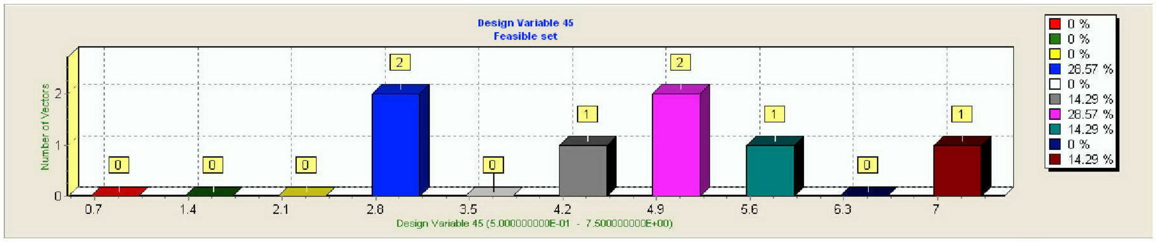

Figure 412 Design Var.45 – SELECTG, DISCRETE, Feasible Set Histogram, 1st Opt.

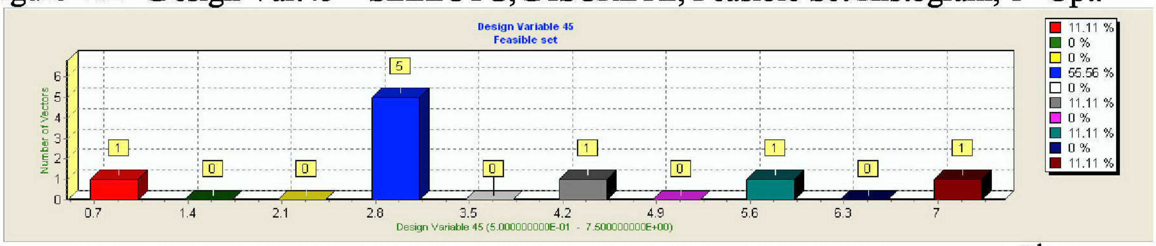

Figure 413 Design Var.45 – SELECTG, DISCRETE, Feasible Set Histogram, 2nd Opt.

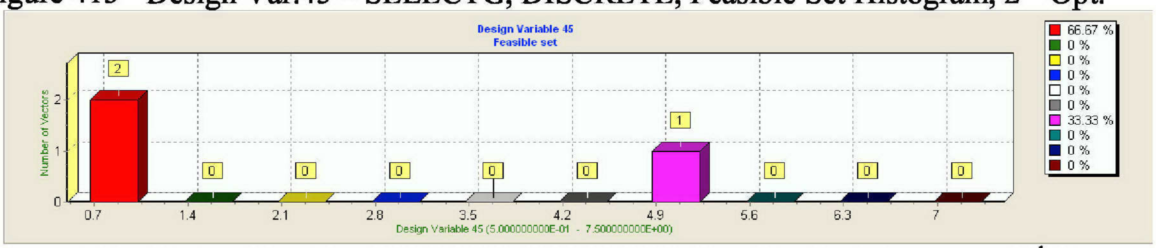

Figure 414 Design Var.45 – SELECTG, DISCRETE, Feasible Set Histogram, 3rd Opt

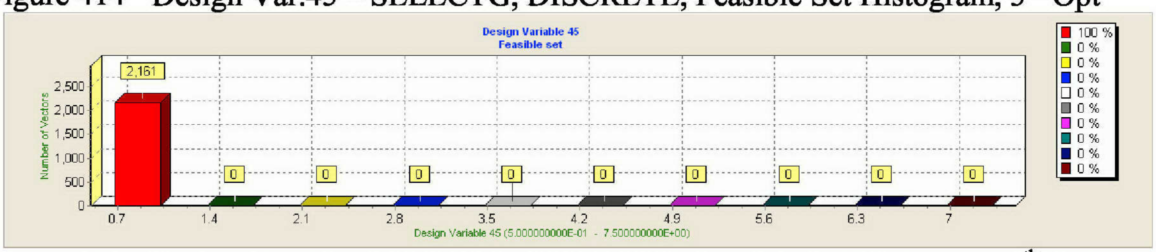

Figure 415 Design Var.45 – SELECTG, DISCRETE, Feasible Set Histogram, 4th Opt.

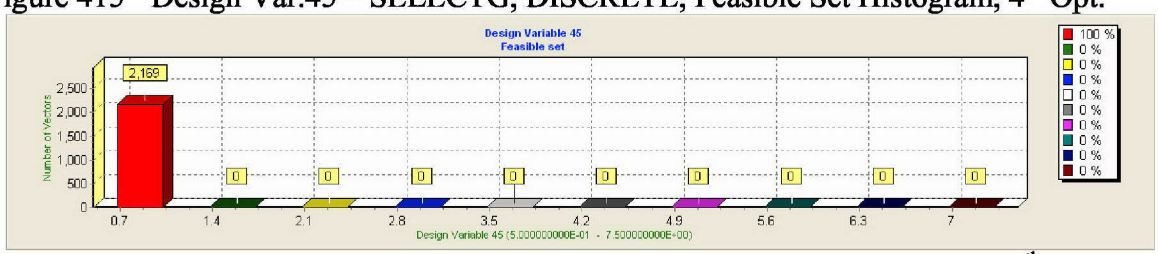

Figure 416 Design Var.45 – SELECTG, DISCRETE, Feasible Set Histogram, 5th Opt.

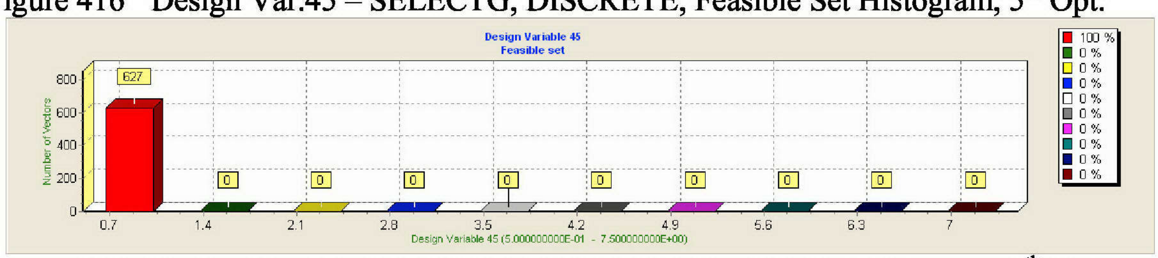

Figure 417 Design Var.45 – SELECTG, DISCRETE, Feasible Set Histogram, 6th Opt.

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APPENDIX N. THE DEPENDENCY OF CRITERION 5 ON DESIGN VARIABLES FOR PARETO OPTIMAL SOLUTION #32921 (MIT MODEL) – 1ST OPTIMIZATION

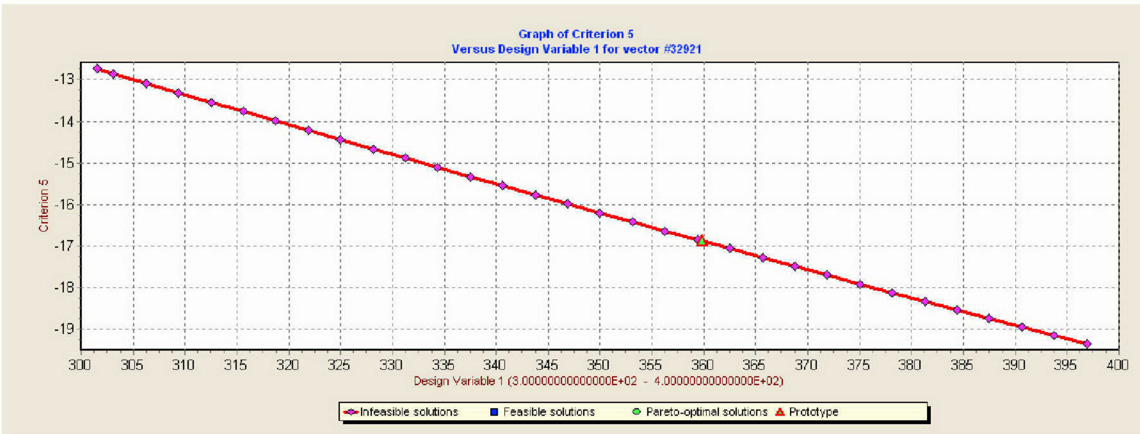

Figure 418 The Dependency of Criterion 5 on Design Variable 1, 1st Opt.

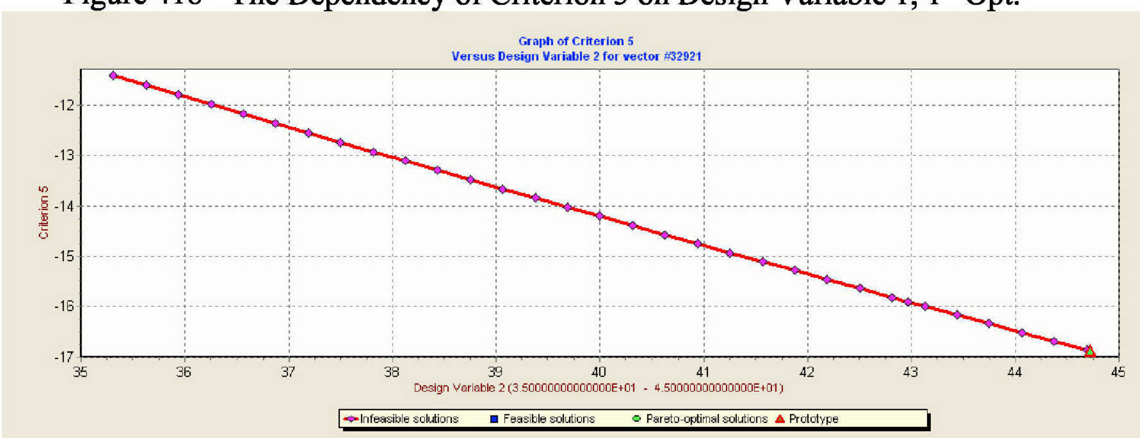

Figure 419 The Dependency of Criterion 5 on Design Variable 2, 1st Opt.

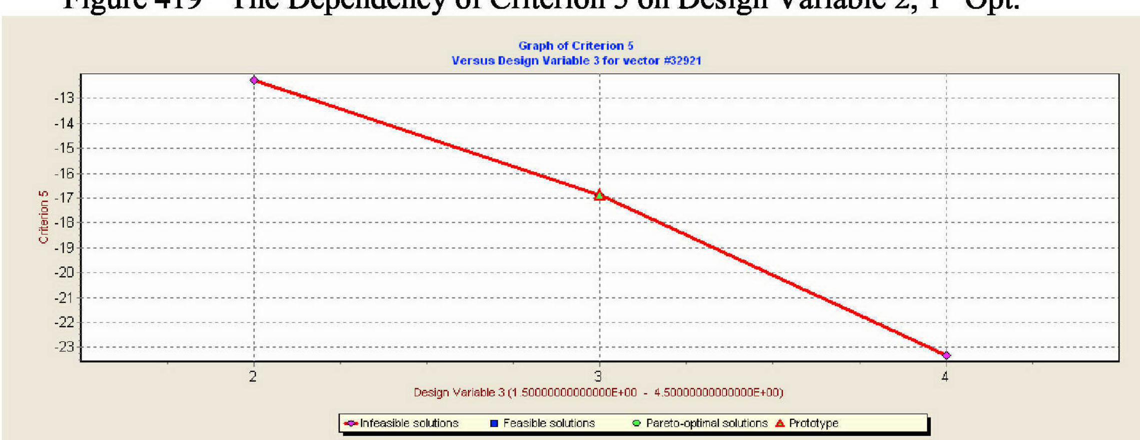

Figure 420 The Dependency of Criterion 5 on Design Variable 3, 1st Opt.

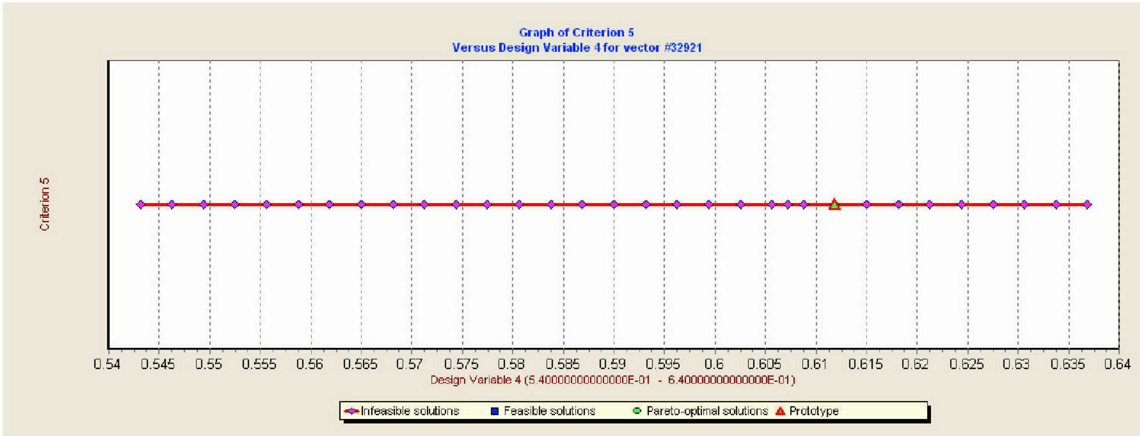

Figure 421 The Dependency of Criterion 5 on Design Variable 4, 1st Opt.

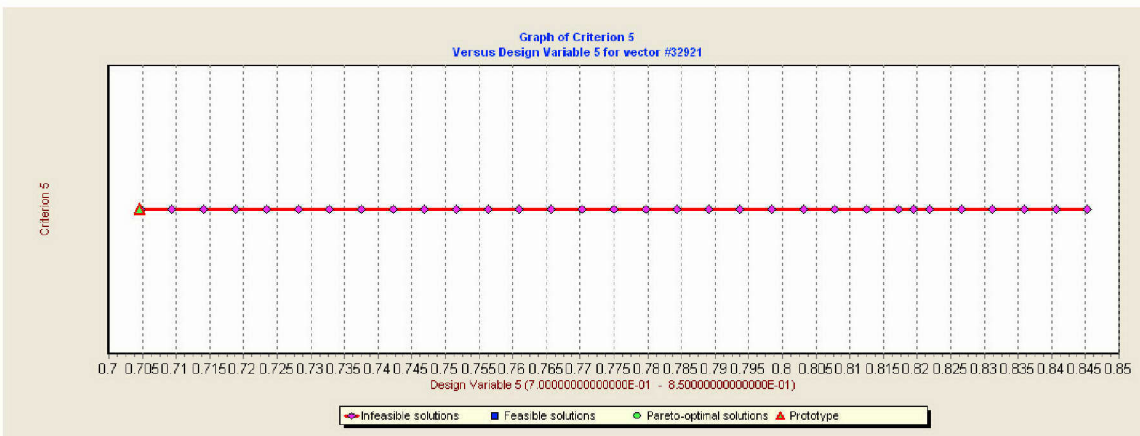

Figure 422 The Dependency of Criterion 5 on Design Variable 5, 1st Opt.

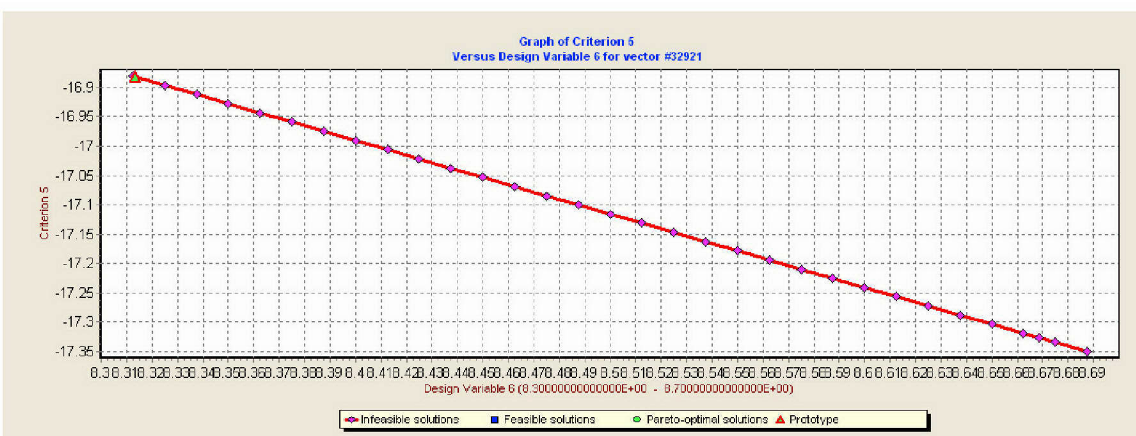

Figure 423 The Dependency of Criterion 5 on Design Variable 6, 1st Opt.

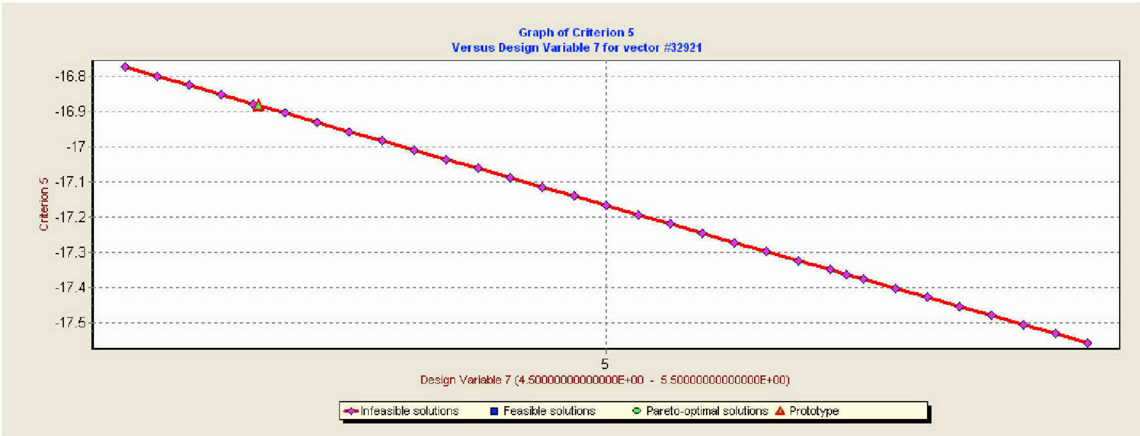

Figure 424 The Dependency of Criterion 5 on Design Variable 7, 1st Opt.

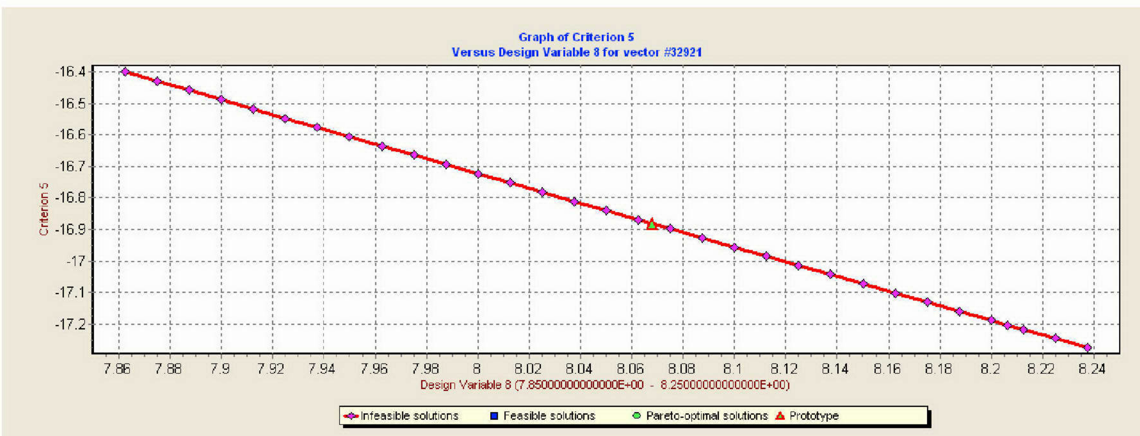

Figure 425 The Dependency of Criterion 5 on Design Variable 8, 1st Opt.

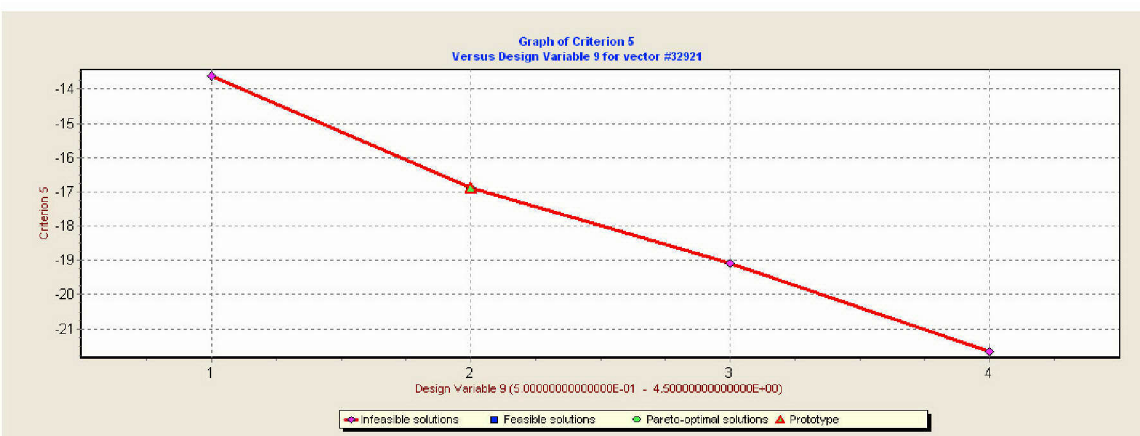

Figure 426 The Dependency of Criterion 5 on Design Variable 9, 1st Opt.

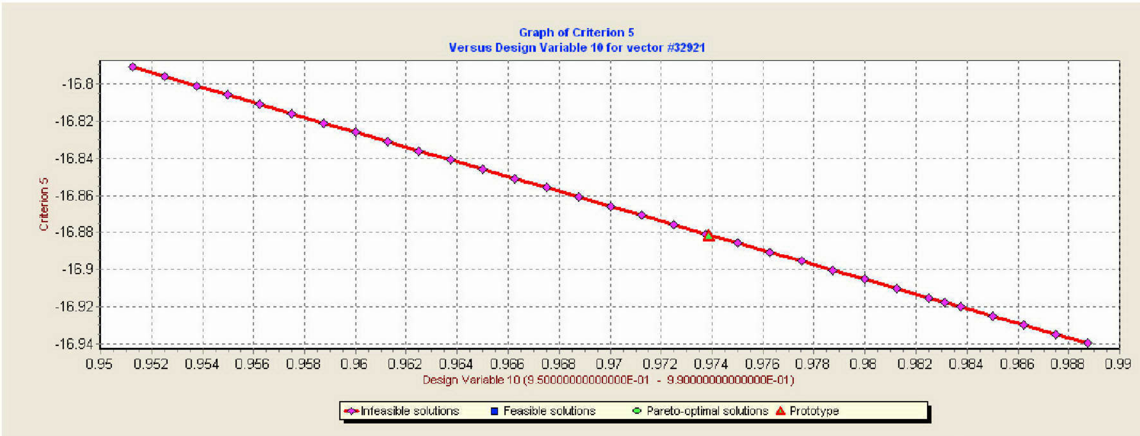

Figure 427 The Dependency of Criterion 5 on Design Variable 10, 1st Opt.

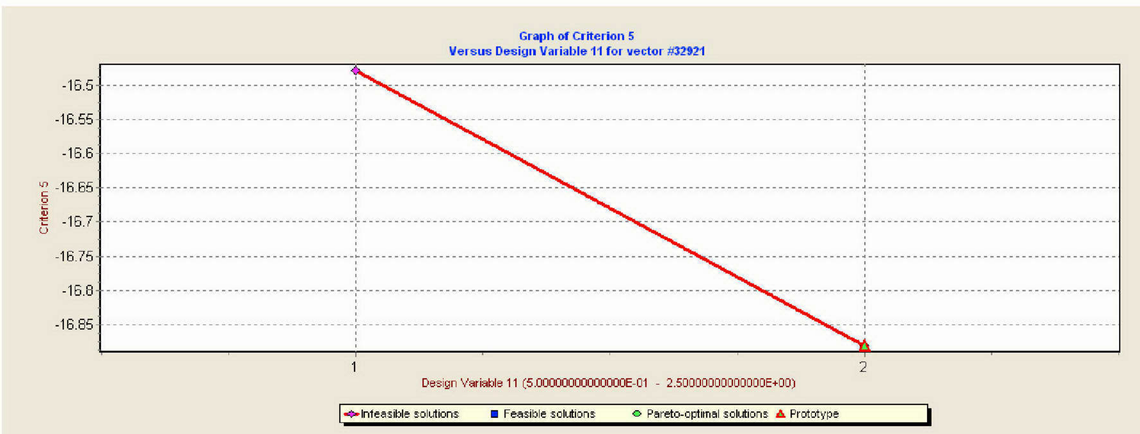

Figure 428 The Dependency of Criterion 5 on Design Variable 11, 1st Opt.

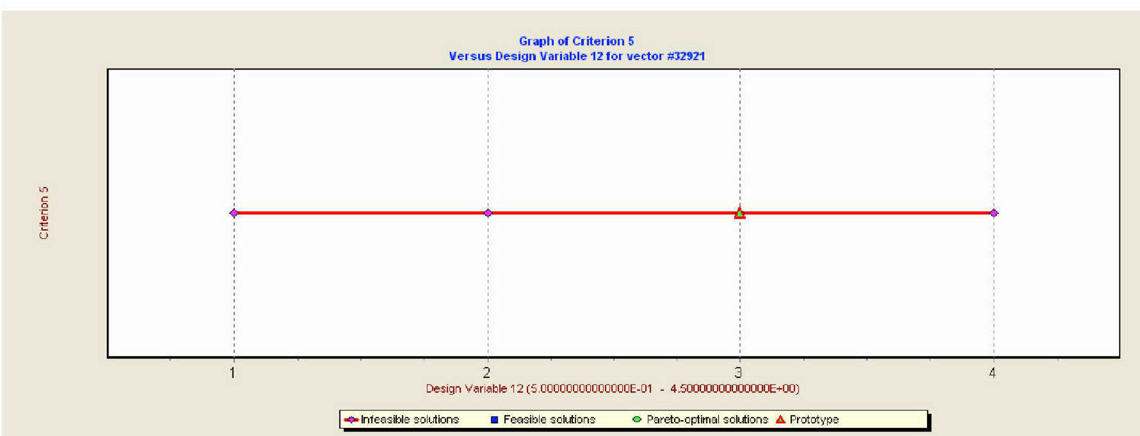

Figure 429 The Dependency of Criterion 5 on Design Variable 12, 1st Opt.

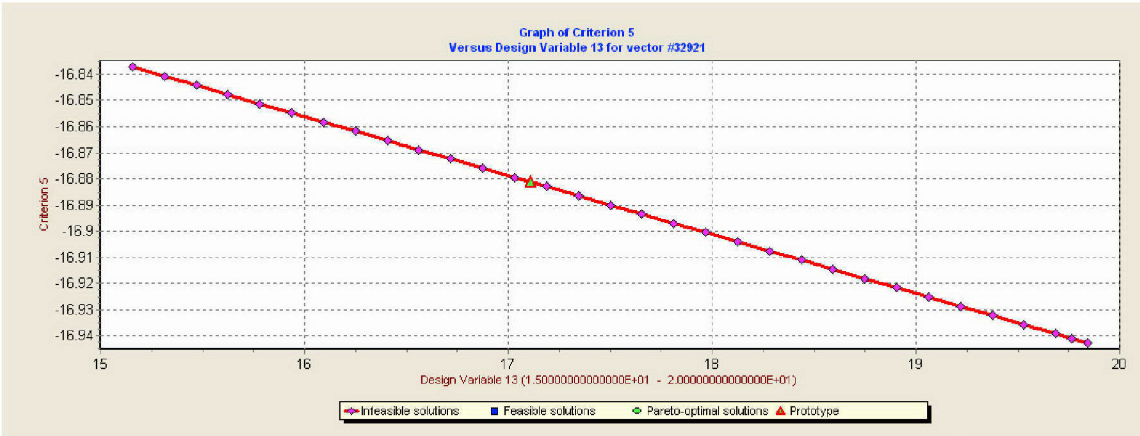

Figure 430 The Dependency of Criterion 5 on Design Variable 13, 1st Opt.

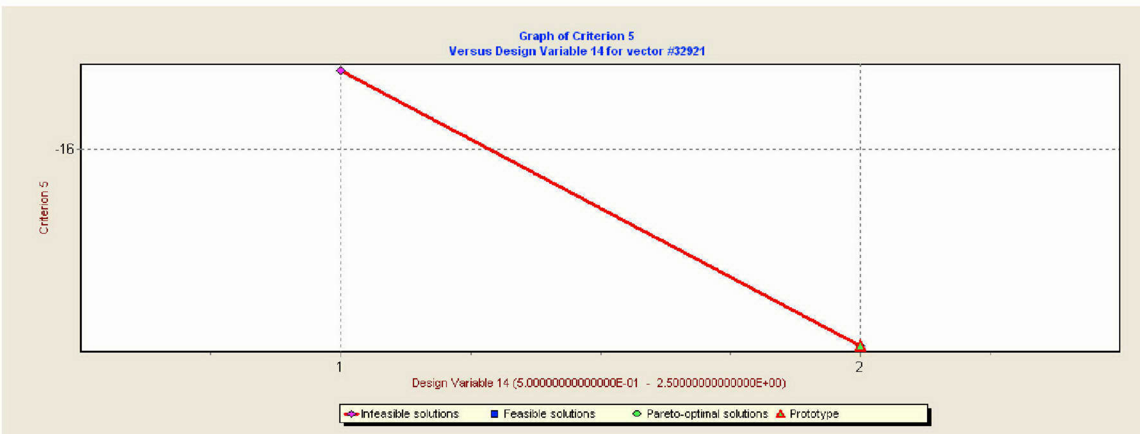

Figure 431 The Dependency of Criterion 5 on Design Variable 14, 1st Opt.

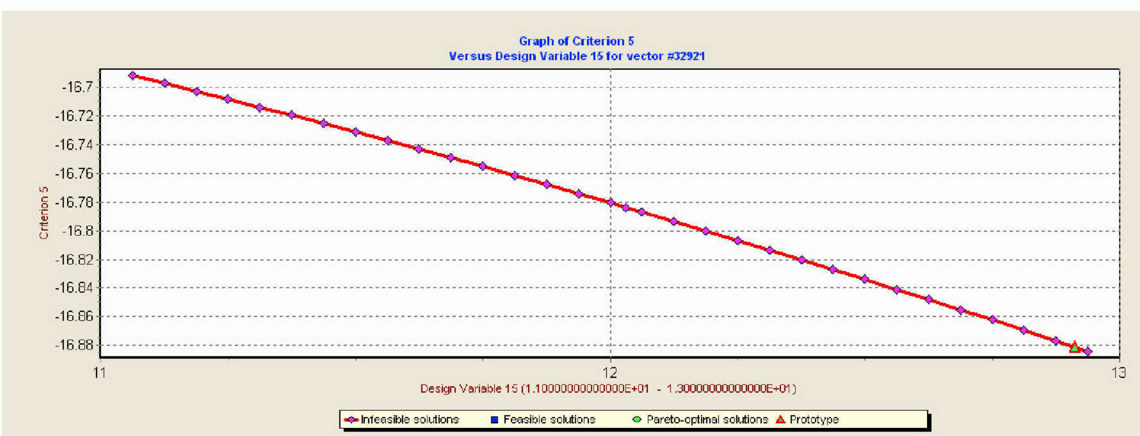

Figure 432 The Dependency of Criterion 5 on Design Variable 15, 1st Opt.

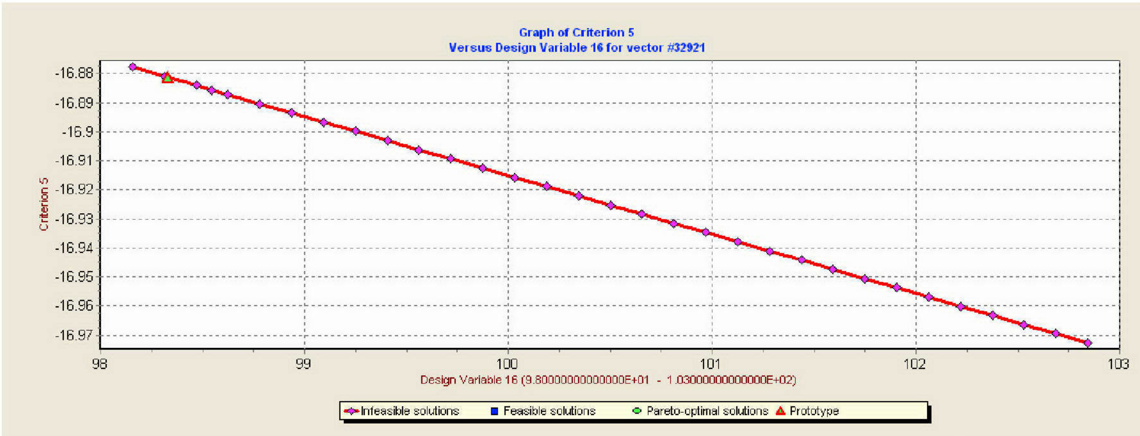

Figure 433 The Dependency of Criterion 5 on Design Variable 16, 1st Opt.

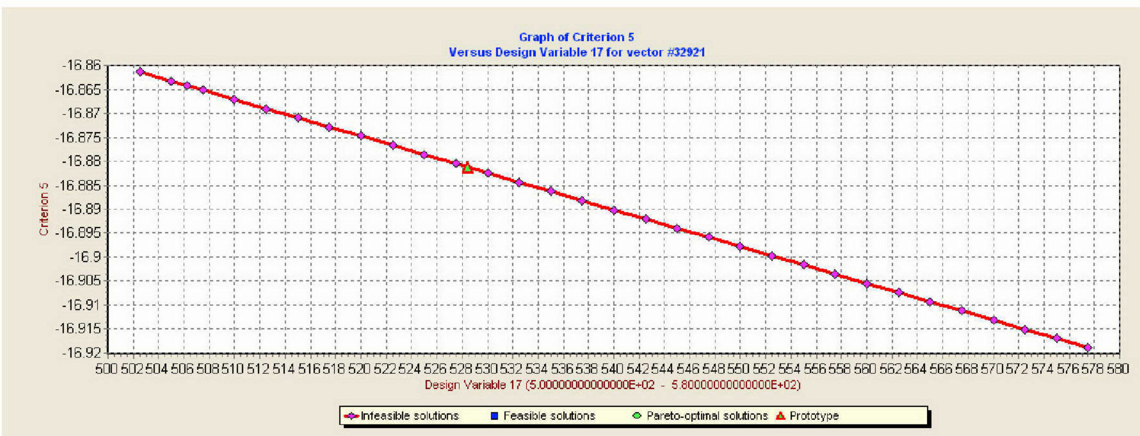

Figure 434 The Dependency of Criterion 5 on Design Variable 17, 1st Opt.

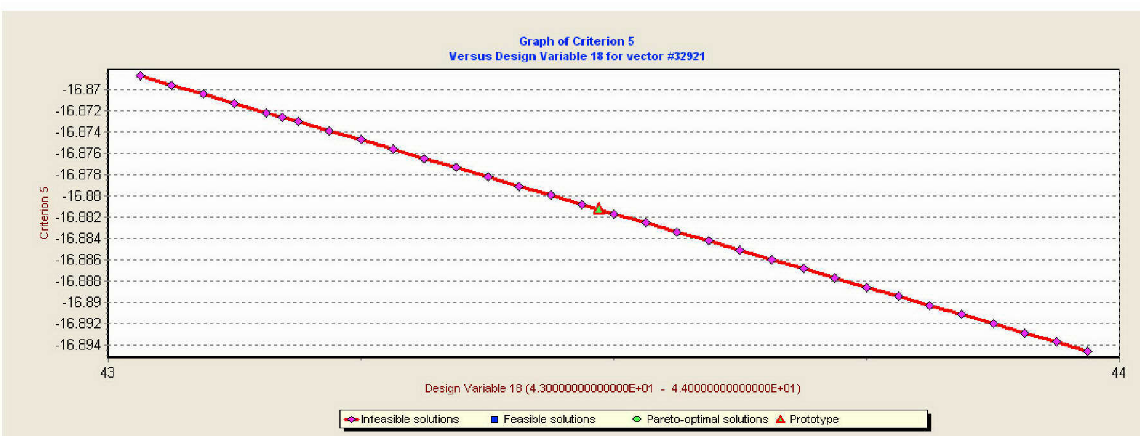

Figure 435 The Dependency of Criterion 5 on Design Variable 18, 1st Opt.

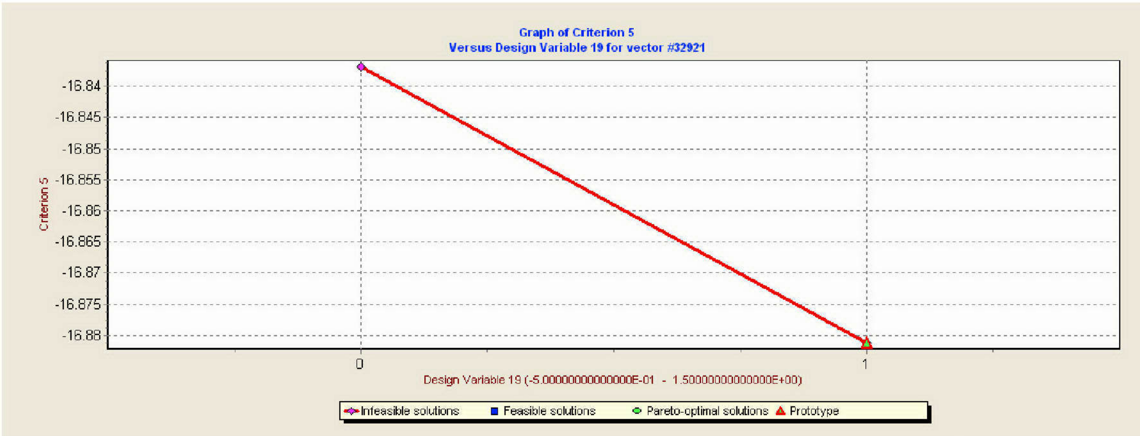

Figure 436 The Dependency of Criterion 5 on Design Variable 19, 1st Opt.

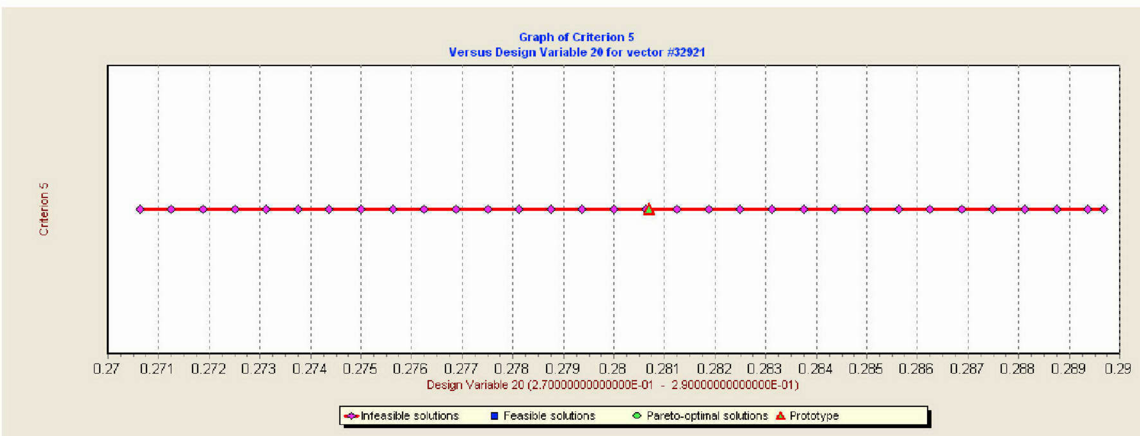

Figure 437 The Dependency of Criterion 5 on Design Variable 20, 1st Opt.

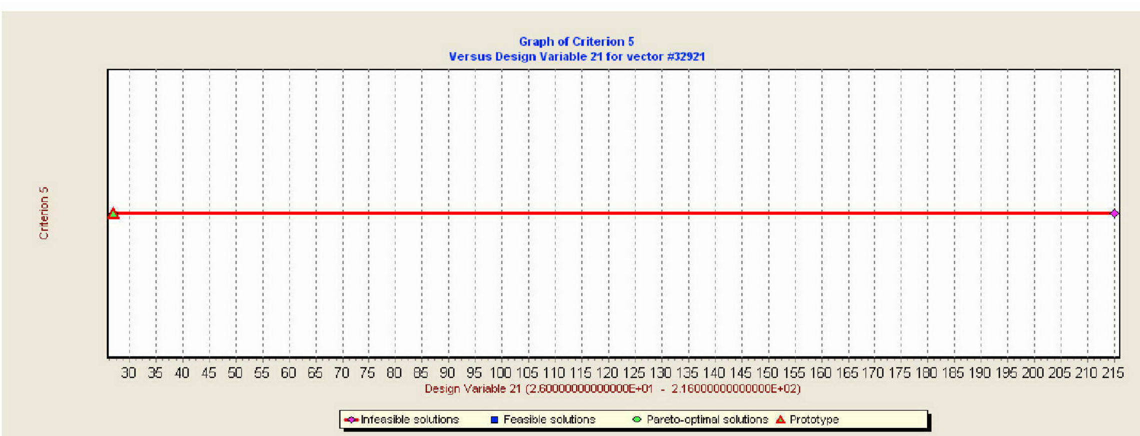

Figure 438 The Dependency of Criterion 5 on Design Variable 21, 1st Opt.

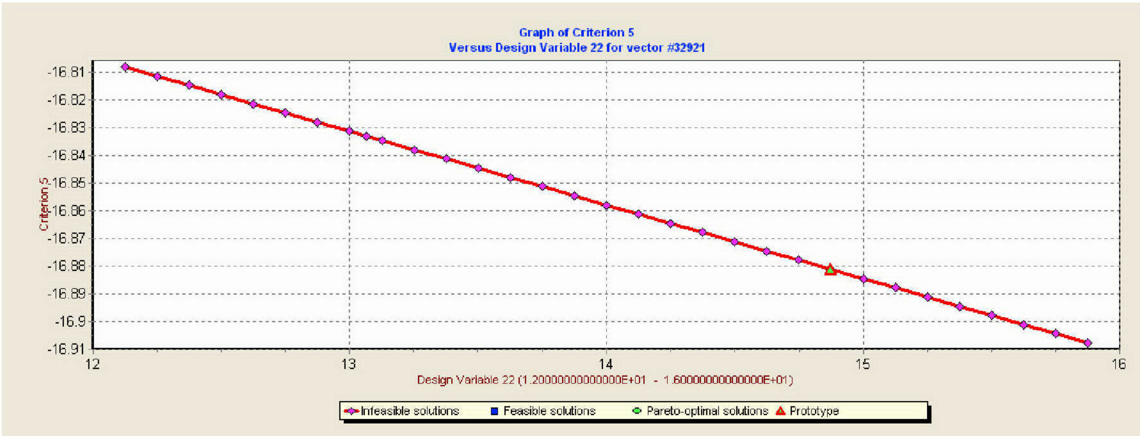

Figure 439 The Dependency of Criterion 5 on Design Variable 22, 1st Opt.

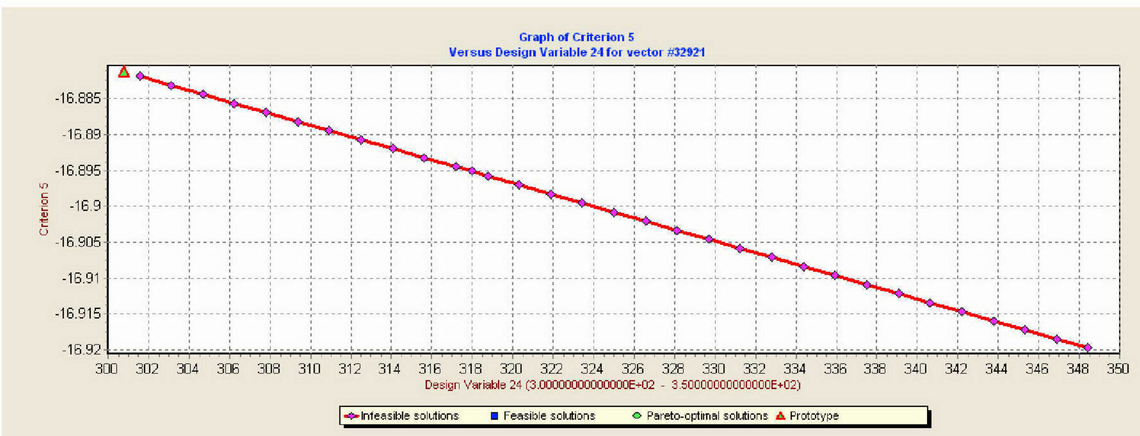

Figure 440 The Dependency of Criterion 5 on Design Variable 24, 1st Opt.

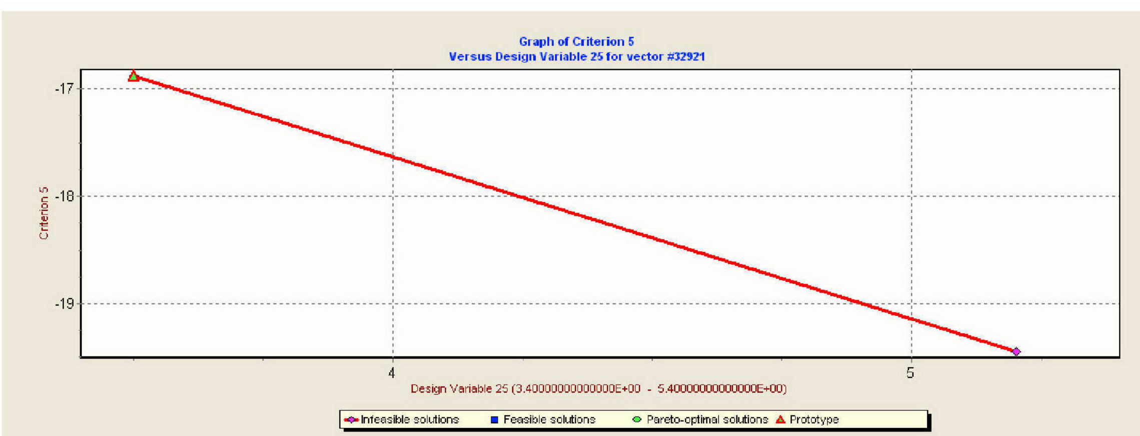

Figure 441 The Dependency of Criterion 5 on Design Variable 25, 1st Opt.

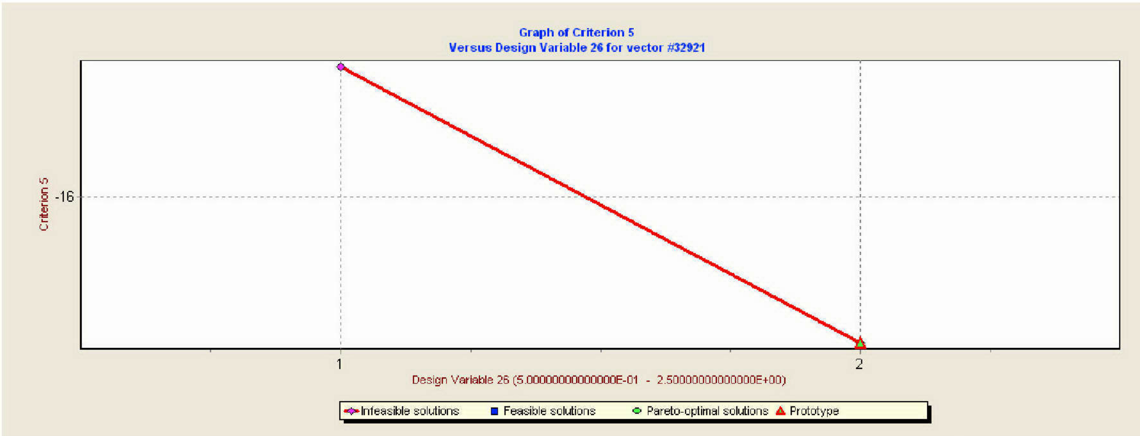

Figure 442 The Dependency of Criterion 5 on Design Variable 26, 1st Opt.

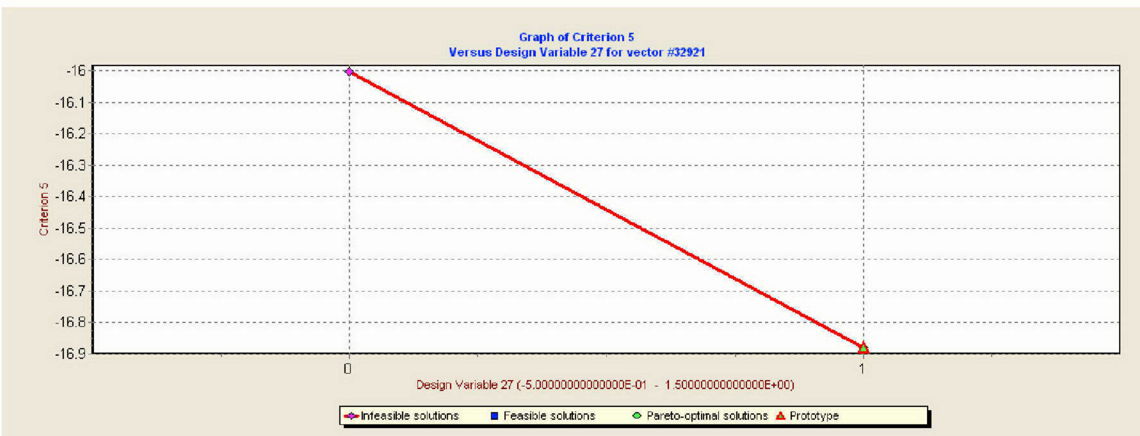

Figure 443 The Dependency of Criterion 5 on Design Variable 27, 1st Opt.

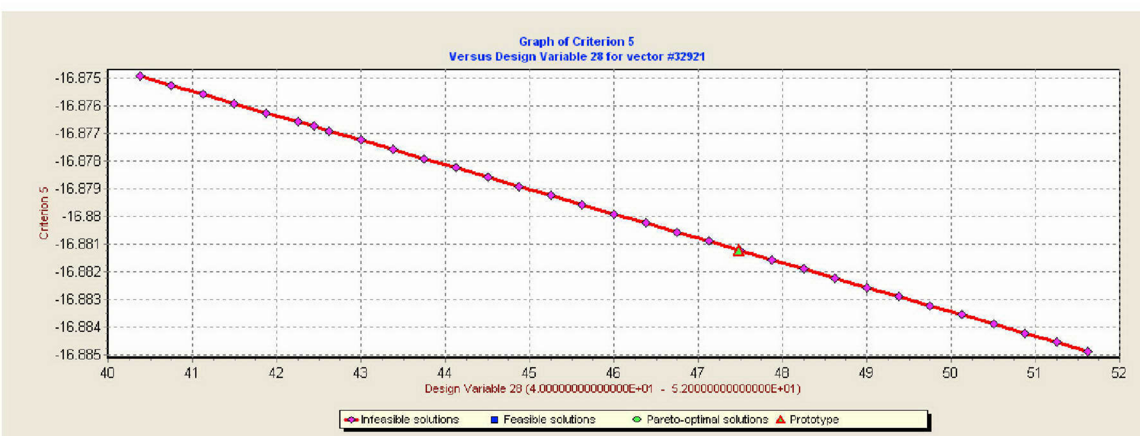

Figure 444 The Dependency of Criterion 5 on Design Variable 28, 1st Opt.

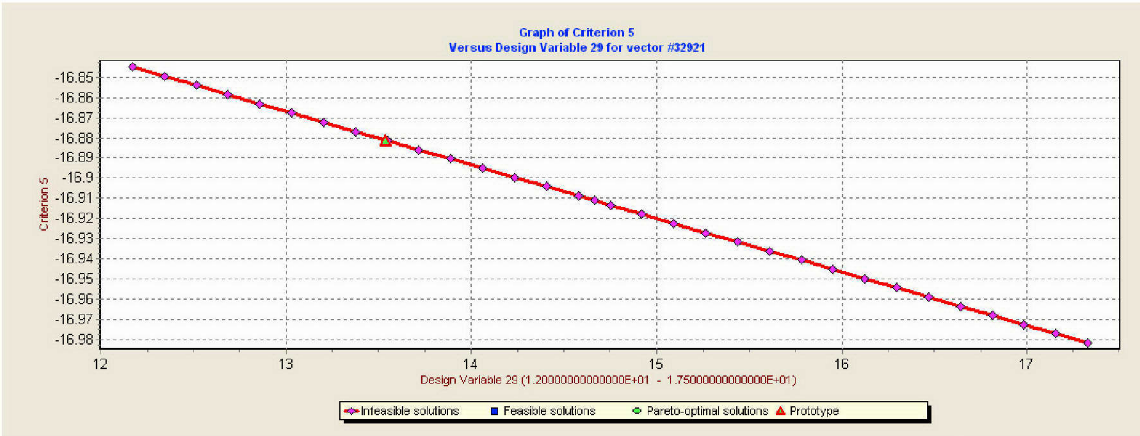

Figure 445 The Dependency of Criterion 5 on Design Variable 29, 1st Opt.

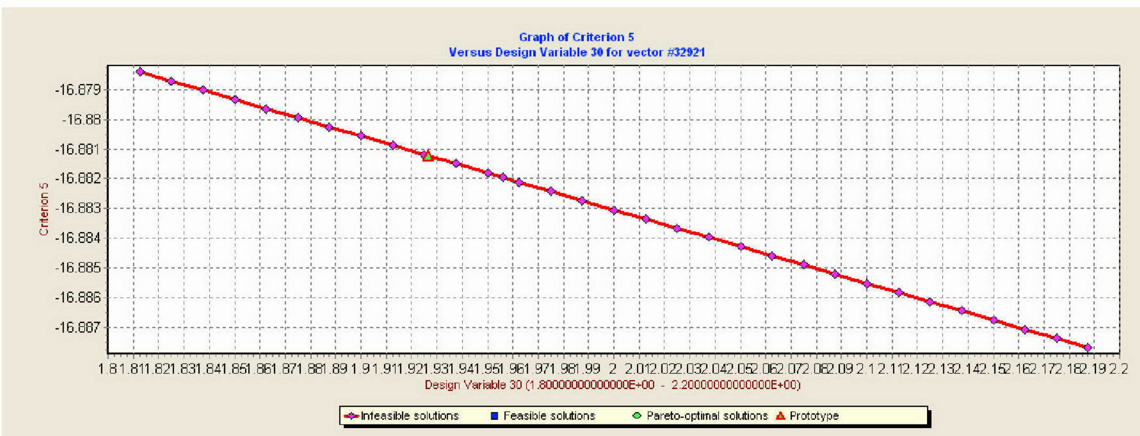

Figure 446 The Dependency of Criterion 5 on Design Variable 30, 1st Opt.

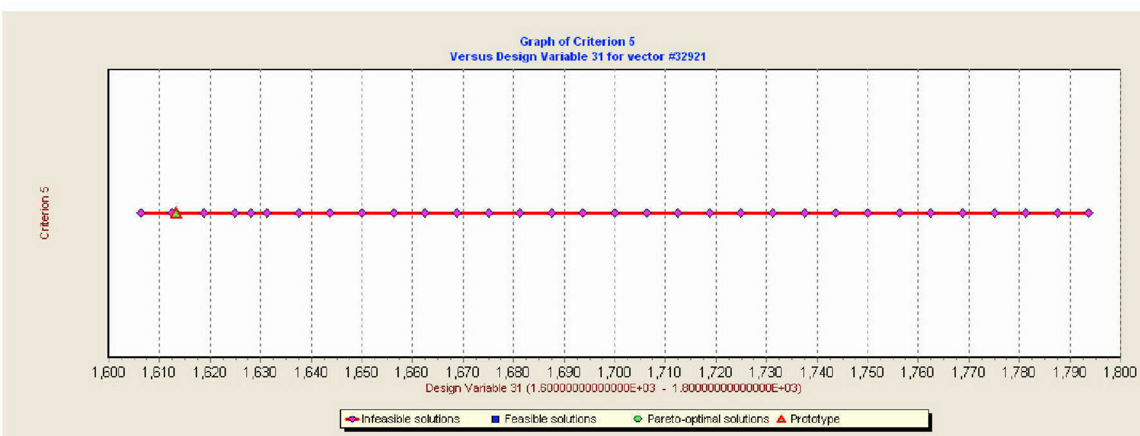

Figure 447 The Dependency of Criterion 5 on Design Variable 31, 1st Opt.

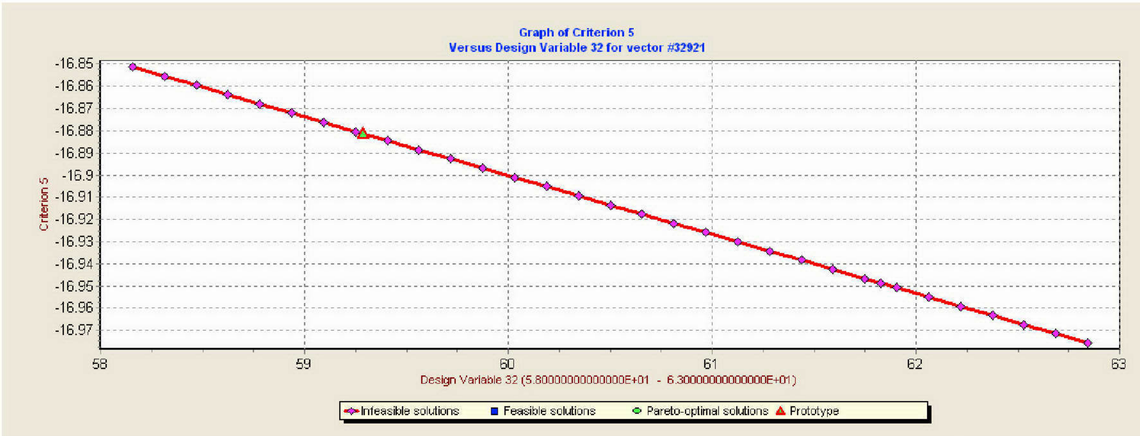

Figure 448 The Dependency of Criterion 5 on Design Variable 32, 1st Opt.

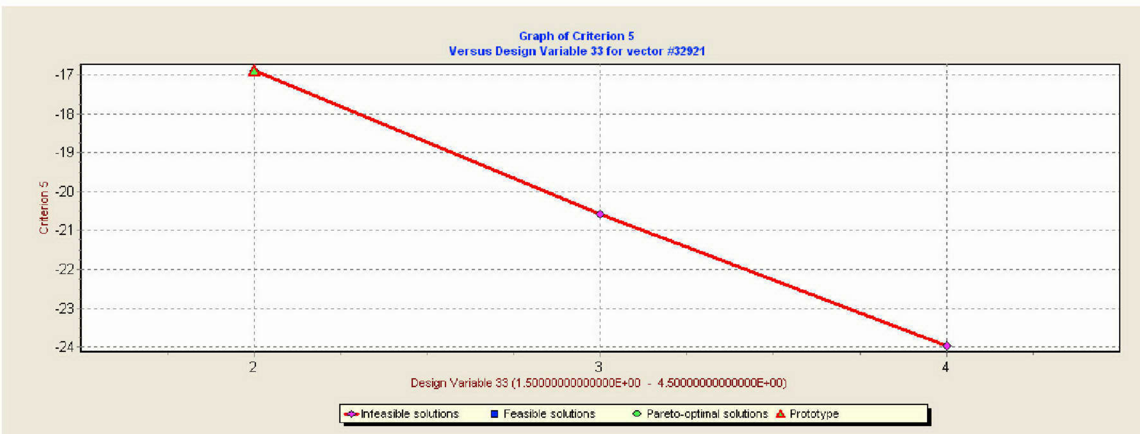

Figure 449 The Dependency of Criterion 5 on Design Variable 33, 1st Opt.

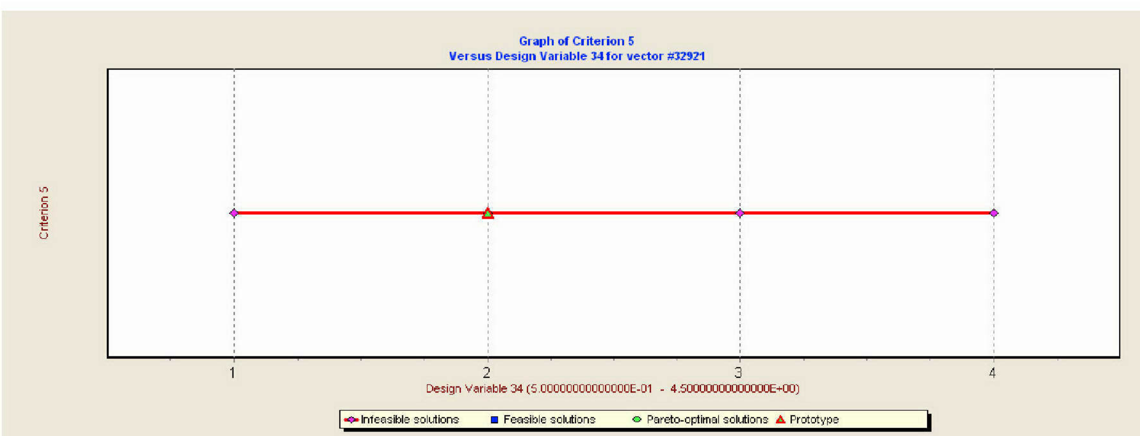

Figure 450 The Dependency of Criterion 5 on Design Variable 34, 1st Opt.

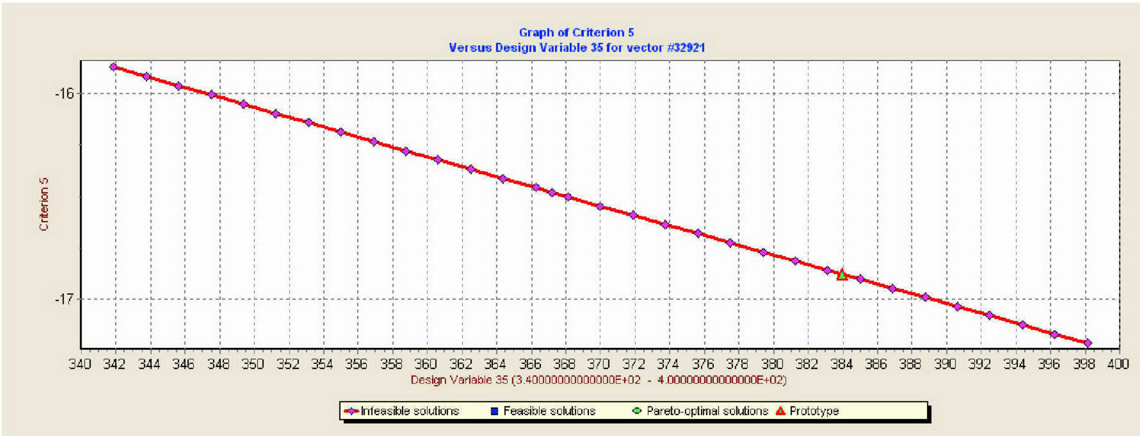

Figure 451 The Dependency of Criterion 5 on Design Variable 35, 1st Opt.

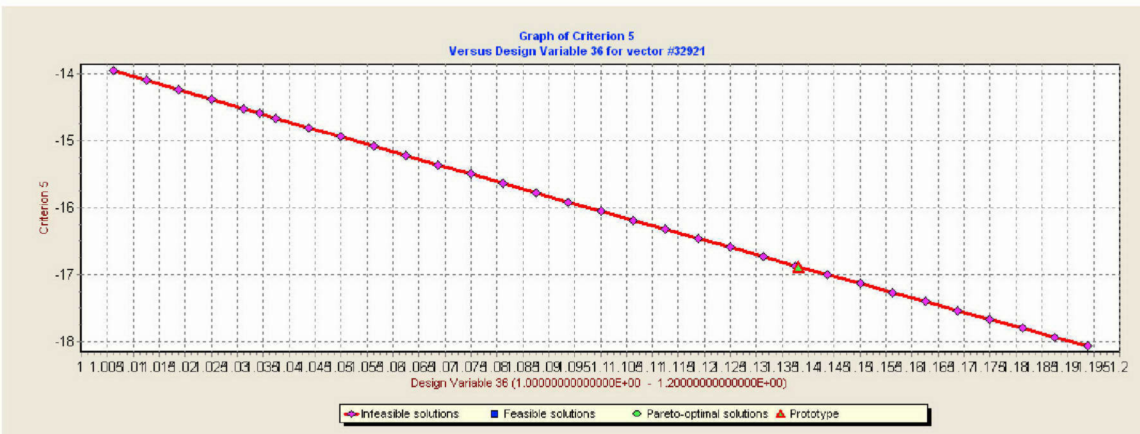

Figure 452 The Dependency of Criterion 5 on Design Variable 36, 1st Opt.

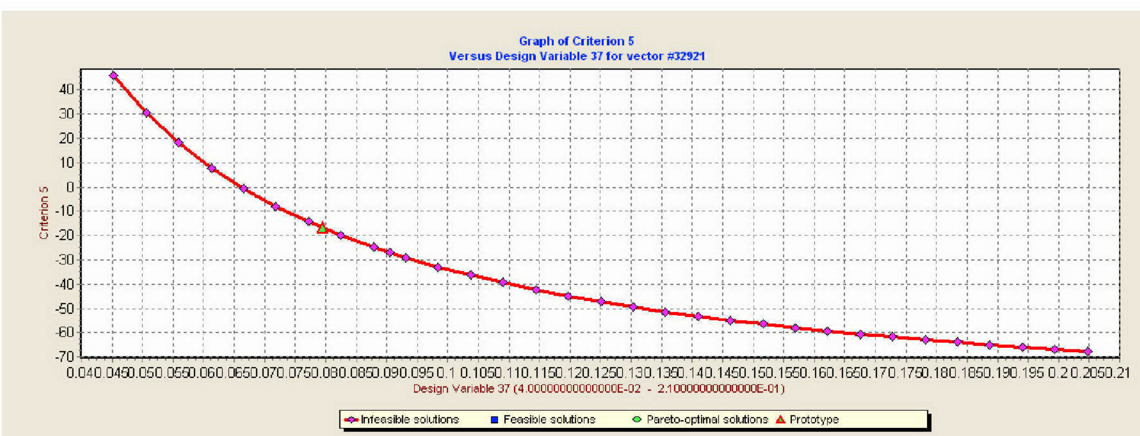

Figure 453 The Dependency of Criterion 5 on Design Variable 37, 1st Opt.

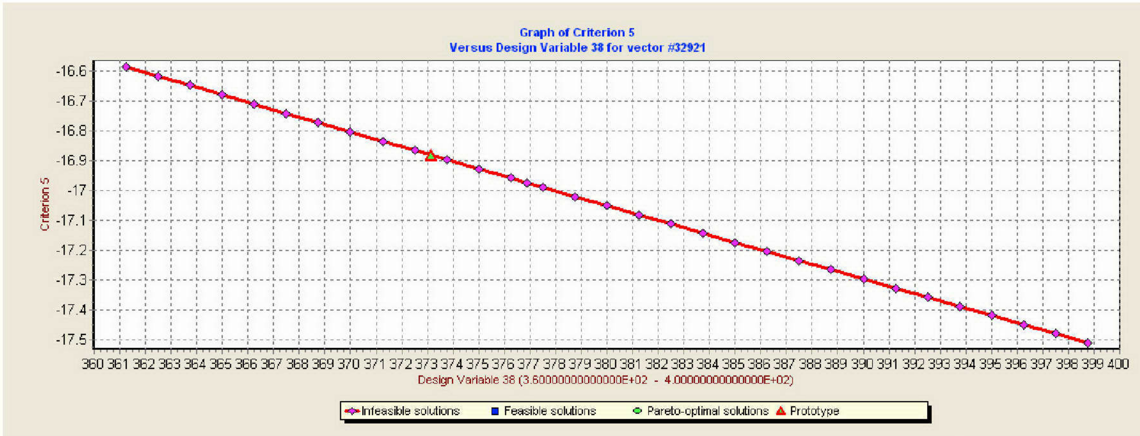

Figure 454 The Dependency of Criterion 5 on Design Variable 38, 1st Opt.

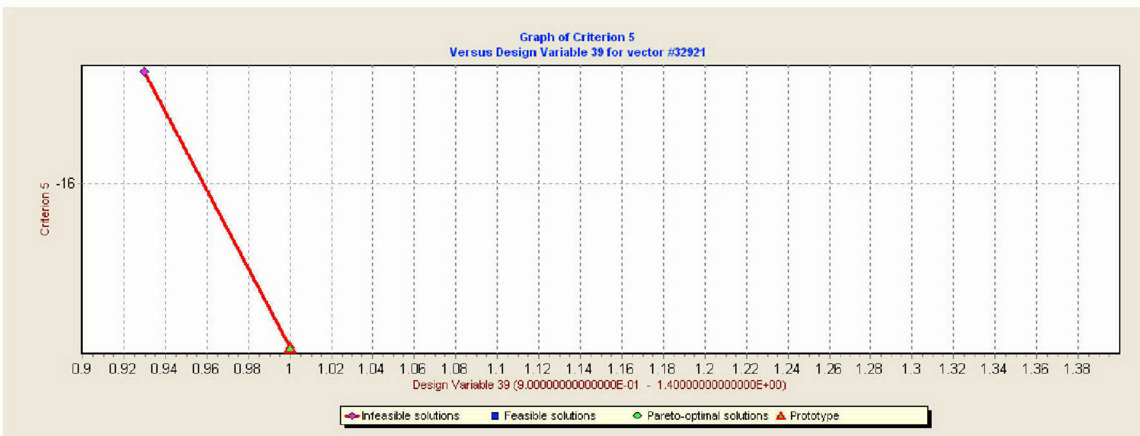

Figure 455 The Dependency of Criterion 5 on Design Variable 39, 1st Opt.

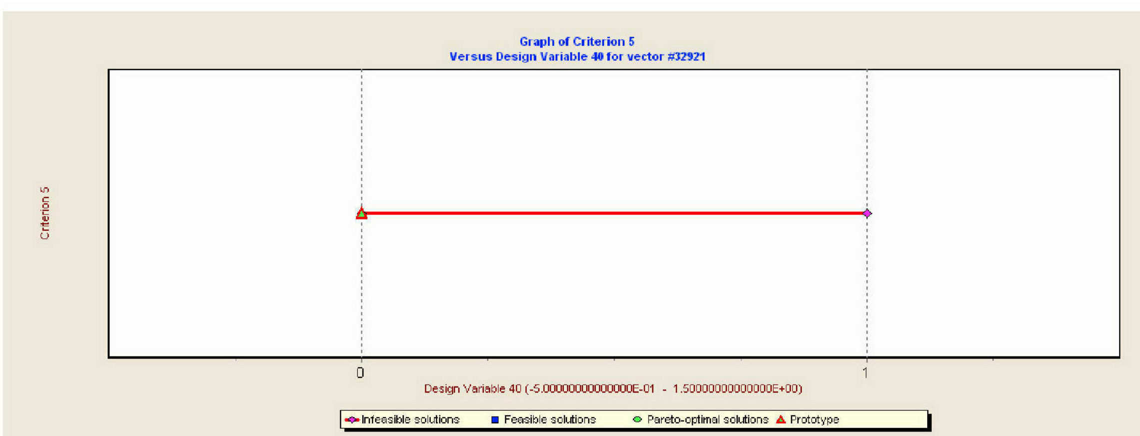

Figure 456 The Dependency of Criterion 5 on Design Variable 40, 1st Opt.

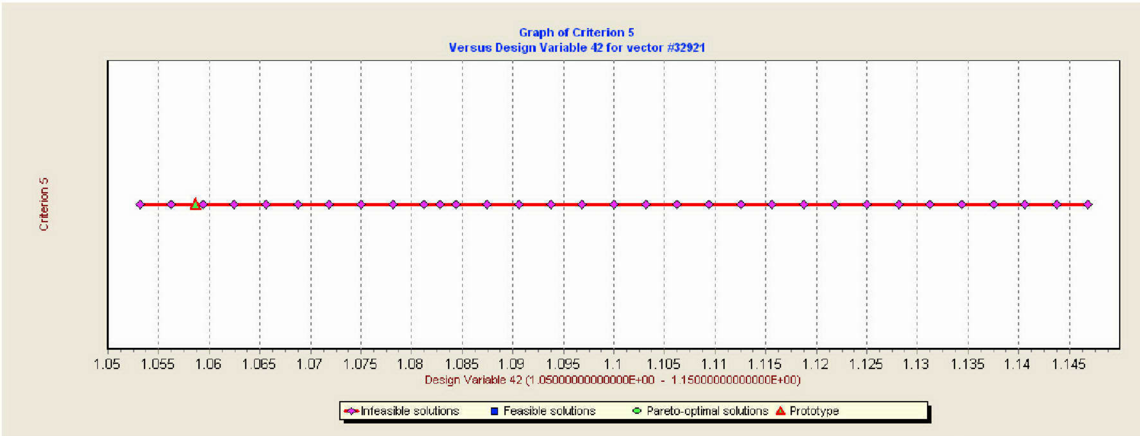

Figure 457 The Dependency of Criterion 5 on Design Variable 42, 1st Opt.

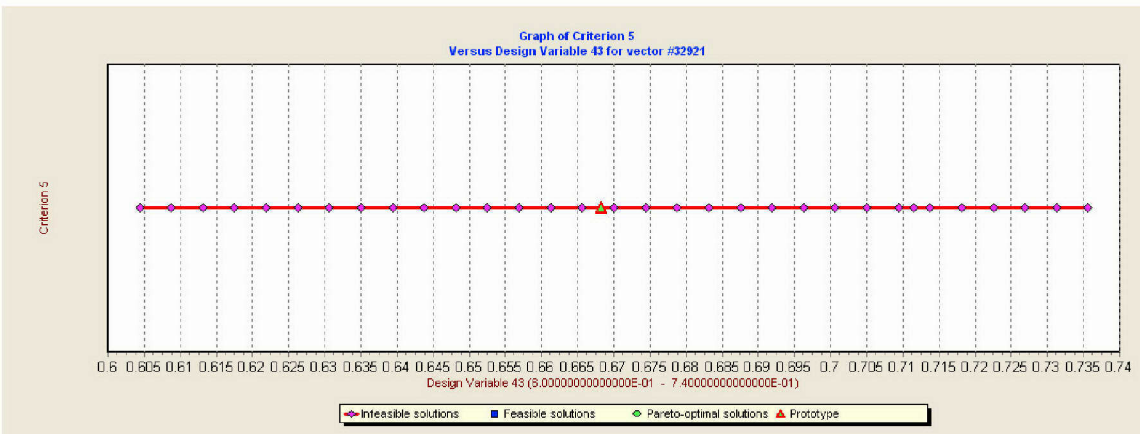

Figure 458 The Dependency of Criterion 5 on Design Variable 43, 1st Opt.

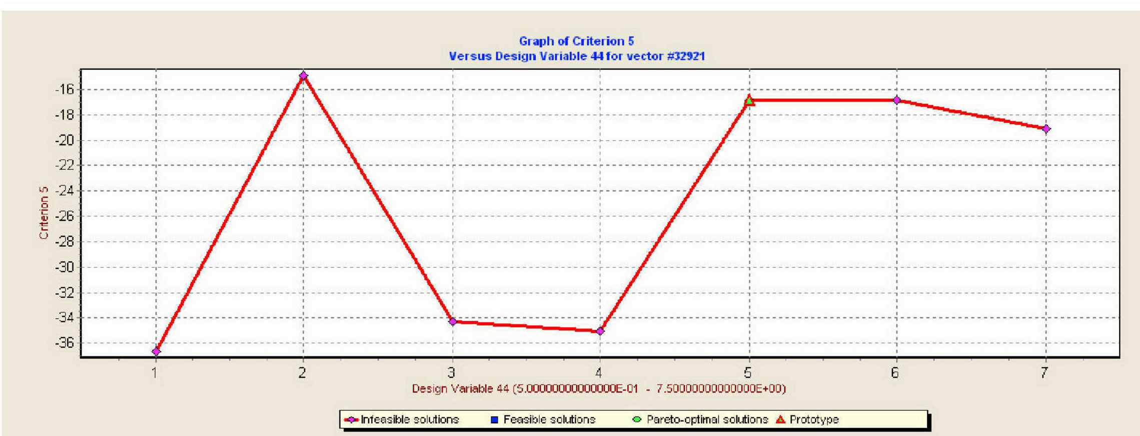

Figure 459 The Dependency of Criterion 5 on Design Variable 44, 1st Opt.

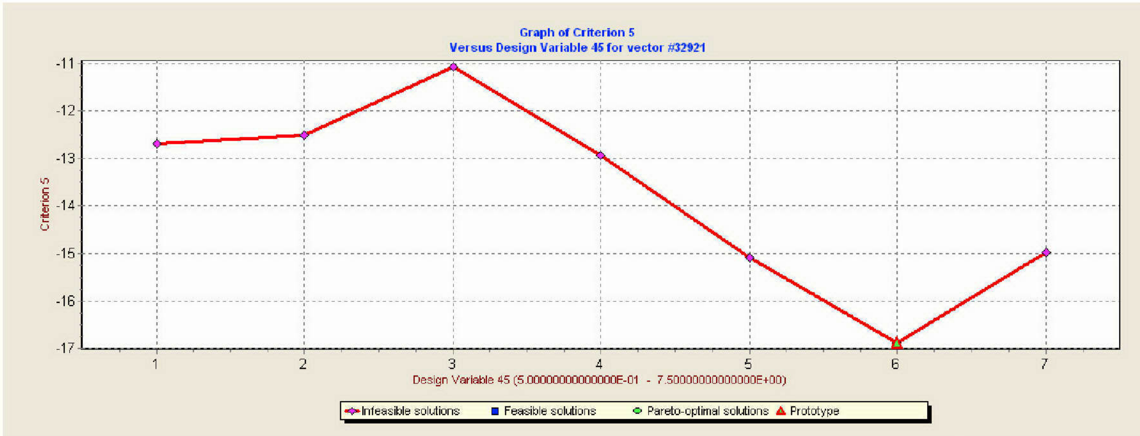

Figure 460 The Dependency of Criterion 5 on Design Variable 45, 1st Opt.

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